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38

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Errata and Additional Comments and Discussion on:

Evaluation of Nitrogen Oxide Emission Factors for Heavy-Duty
Diesel Trucks Based on Ambient Air Measurements

by

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Disclaimer:

The U.S. Environmental Protection Agency (USEPA) funded the research described here under assistance agreement CR 823020 to the Georgia Tech Research Corporation. The contents of this paper reflect the view of the author who is responsible for the facts and accuracy of the data present herein. The contents do not necessarily reflect the official views or policies of the USEPA, nor does this document constitute a standard, specification, or regulation.

Background:

The research described in the attached thesis by Mr. Chad Garretson was pursuant to the testing of the Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE) developed by the Georgia Tech Research Partnership under EPA cooperative agreement number CR 823020. As a degree thesis, this work underwent Georgia Institute of Technology peer review as an academic work and was approved by the committee as presented in this report. Upon completion, the thesis was subject to additional peer review by U.S. EPA under terms of the cooperative agreement. This review resulted in several comments that are addressed or clarified in this supplement to Mr. Garretson's thesis.

Comments:

Comment 1: The authors should clarify that this study was pre-defeat-device removal.

So Noted.

Comment 2: A more recent citation to the Trends reports should be included.

The most recent version of the Trends report can be downloaded from the URL http://www.epa.gov/oar/aqtrnd**/ *where ** is the two digit code for the previous year.*

Comment 3: The disclaimer should be more explicit.

The disclaimer is given on the first page of this supplement.

Comment 4: Data referenced from other reports has not been reviewed for accuracy.

Data presented from other sources is presented for purposes of comparison to results described here and is not meant to imply that these other data sources are either more or less reliable than the results presented here.

Comment 5: EPA feels that it can effectively evaluate the impact of control measures given currently available data contrary to the statement in the first paragraph of the summary.

Virtually all-available in-use data on heavy-duty diesel emissions comes from either instrumented vehicles or engine dynamometer testing. The extent to which these results mimic real world conditions is uncertain. This work was specifically designed as a "first cut" to evaluate the validity of this core assumption. This work, in fact, suggests that the existing data are, in fact, substantially reflective of observed on-road emissions.

Comment 6: What EPA Document is referenced as U.S. EPA 1995 on page 11?

This is the emissions Trends report discussed in comment 2.

Comment 7: On page 13, the position that EPA has not placed severe restrictions on diesel engine emissions should be stated as the author's opinion and not as official agency policy.

This is true and is noted in the disclaimer accompanying this report.

Comment 8: On page 19, the sentence "Whether or not these operating modes represent actual vehicle operation is also highly unlikely" should be restated.

It should be stated as : "In the author's opinion, it is highly unlikely that these operating modes represent actual vehicle operation."

Comment 9: On page 22, more data should be provided to support the statement that the new dynamometer test cycle may not be representative of actual driving conditions.

It should be stated as: "In the author's opinion, there is yet insufficient evidence to conclude that the new dynamometer test cycle is representative of actual in-use driving behavior."

Comment 10: On page 24, it should be noted that instrumented trucks are "one of the best approaches" rather than "the best approach".

So noted.

Comment 11: On page 24, it should be noted that the data collected from the roadway approach represent fleet averages rather than data from individual vehicles.

So noted.

Comment 12: On page 28, the last paragraph state that the traffic flows from west to east and this is inconsistent with the figure.

The text is incorrect. The traffic flows from east to west in the study zone.

Comment 13: On page 80, Shouldn't rolling averages have the same duration to relate two different sets of data? Shouldn't data be drawn from the same interval or segment?

If the data had the same intrinsic integration period, then the rolling averages should have the same smoothing period. In practice, with variable wind speeds (and thus variable delay time) and fluctuating traffic volumes the "best fit" smoothing is largely empirically derived.

Comment 14: On page 86 why were the observed concentrations low?

Concentrations were depressed for a variety of reasons including low traffic volume due to poor weather and higher than usual inversion heights.

Comment 15: On page 87, If carbon dioxide and NO have inconsistent rates of change, this will have an adverse impact on the correlation of these variables.

In all cases the high NO concentrations and rapid surface loss leads to depletion of ozone concentrations in the roadway study area. Under these conditions the chemical lifetime of both gases are much longer than the transport times and thus the observed ratios should be consistent with those of the sources.

Comment 16: On page 88, Did the ratios of d NO/ d CO_2 versus fleet composition also yield statistically insignificant results?

Yes.

Comment 17: On page 98, What rate equations were employed to determine $NO \rightarrow NO_2$ conversion rates?

As mentioned in comment 15 above, the conversion rates from NO to NO_2 were very slow compared to transport. This was confirmed by observation of NO_x ($NO + NO_2$) concentrations in conjunction with the NO measurements.

Comment 18: On page 138, What is the basis for the statement that no significant difference between east- and west-bound truck GVW is expected? Is this derived from visual inspection of whether the trucks were full or empty?

No. This assessment is based on similar truck stop studies conducted earlier on I-75 near Atlanta that showed no measurable difference in weight distributions entering and leaving the city. This certainly does not preclude a difference on the I-20 corridor but we do feel that these observations make such a difference less likely.

Evaluation of Nitrogen Oxide Emission Factors for Heavy-Duty Diesel Trucks Based on Ambient Air Measurements

A Thesis
Presented to
The Academic Faculty

by

Chad C. Garretson

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Environmental Engineering

Georgia Institute of Technology
June, 1997

Evaluation of Nitrogen Oxide Emission Factors for Heavy-Duty
Diesel Trucks Based on Ambient Air Measurements

Approved:

Michael O. Rodgers, Chairman

Randall L. Guensler

James A. Mulholland

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Date Approved:

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This project would not have been possible without the important contributions of several individuals, namely;. Jim Pearson, for his support throughout all phases of this work; Dr. Ted Russell, for his assistance with data analysis; Dr. Randy Guensler, for his insightful comments and library of references; and Dr. Jim Mulholland, for not only his valued participation, but also the guidance he has provided throughout my graduate career. Most importantly however, this thesis would not have been possible were it not for the continued encouragement and direction provided by Dr. Mike Rodgers, for whom I respect greatly.

I would also like to thank the many individuals who assisted with field test efforts, including, Jeral Estupinan, Jeff Cordle, Charlie Meeker, Jose Martinez, Prokofiy Klochko, Vladimir Paderin, Alexander Samoylov, and Chris Riggins. Also, special thanks to Mary Beth Canon for her administrative assistance, and to Machonne Barlow for enduring countless hours reviewing video tapes.

Finally, I would like to thank my parents and family for their loving support over the years, for this is the main reason I was able to participate in this effort. Lisa, my wife, although the timing of this work was less than ideal, you somehow made the experience bearable; I dedicate this thesis to you.

Disclaimer

The U.S. Environmental Protection Agency (USEPA) funded the research described here under assistance agreement CR 823020 to the Georgia Tech Research Corporation. The contents of this paper reflect the view of the author who is responsible for the facts and accuracy of the data present herein. The contents do not necessarily reflect the official views or policies of the USEPA, nor does this document constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

AFR	--	Air-To-Fuel Ratio
AIR		Atmospheric Instrumentation Research Inc.
ANOVA	--	Analysis Of Variance
APPCD	--	Air Pollution Prevention And Control Division
BHP		Brake Horsepower
BSFC	--	Brake Specific Fuel Consumption
CAA	--	Clean Air Act
CARB	--	California Air Resources Board
CEMS	--	Continuous Emissions Monitoring System
CFR	--	U.S. Code Of Federal Regulations
DAS	--	Data Acquisition System
DOT		Department Of Transportation
EMB	--	Emissions Monitoring Branch
EST	--	Eastern Standard Time
FTP	--	Federal Test Procedure
g		grams
GIS	--	Geographical Information System
GVWR	--	Gross Vehicular Weight Rating
HC		Hydrocarbons
HDDV	--	Heavy-Duty Diesel Vehicles
HPMS	--	Highway Performance Monitoring System
LDGV	--	Light-Duty Gasoline Vehicles
mi		mile
lb		pound
mph		miles per hour
NAAQS	--	National Ambient Air Quality Standards
NDIR	--	Non-Dispersive Infrared
NO_X		Nitrogen Oxides
PM	--	Particulate Matter
PVC	--	Poly-Vinyl-Chloride
RPM	--	Revolutions Per Minute
RV	--	Recreational Vehicle
SIP	--	State Implementation Plan
SOP	--	Statement Of Principals
SOS	--	Southern Oxidants Study
TECO		Thermo Environmental Corporation
TIUS	--	Truck Inventory And Use Survey
USEPA	--	United States Environmental Protection Agency
UTPS	--	Urban Transportation Planning System
VMT	--	Vehicle-miles Traveled

SUMMARY

Recently, reductions in NO_X emissions have been identified as the most effective ground-level ozone control strategy for many areas of the country. As a result, urban areas attempting to meet ozone standards are placing greater emphasis on reducing emissions from heavy-duty diesel engines. However, due to the significant amount of uncertainty associated with "in-use" heavy-duty diesel vehicle emission estimates, policy analysts and public decision makers can not effectively evaluate the impact of existing and proposed control measures.

Mobile source emissions are estimated by multiplying emission-producing vehicle activity estimates by activity-specific emission factors. Heavy-duty vehicle emission factors (g/bhp-hr) are developed based on new engine certification test results performed on engine dynamometers. How well emission factors developed based on engine dynamometer tests represent actual "in-use" emissions in not well established. Furthermore, because activity models do not incorporate or estimate bhp-hr (energy), further uncertainty is introduced by the need to convert emission factors into units of g/mi.

This paper introduces a unique method which can be used to evaluate "in-use" NO_X emission factors for heavy-duty vehicles. The method utilizes atmospheric perturbation observations in ambient NO and CO_2 concentration levels near a roadway to estimate fleet-average NO_X emission factors in g/bhp-hr. Modal emission factors (that reflect the operating conditions and driver behavior characteristic to the roadway test location) can be evaluated by estimating the demanded horsepower required for trucks driving through the test site.

Heavy-duty truck emission factors are presented based on sampling performed along an interstate in rural Georgia in October, 1996. As part, emissions from approximately 5,500 heavy-duty trucks were measured during the reported test periods. A baseline fleet-average NO_X emission factor of 6.51 g/bhp-hr was estimated based on the data collected. Modal emission factors (g/hr) were also estimated and results compared favorably to tests performed at the site with an instrumented truck.

CHAPTER I

INTRODUCTION

In 1990, Congress reauthorized and extensively amended the Clean Air Act (CAA) in a third effort to "protect and enhance the quality of the Nation's air resources[1]." These amendments provided another extension for national ambient air quality standards (NAAQS) compliance. Although significant progress has been made in reducing pollutant emissions from most sources, economic growth and development has offset some of these gains. This is especially true in the area of mobile sources.

Of the six "criteria"[2] pollutants for which NAAQS have been established, ground-level ozone has presented the greatest urban challenge. Twenty-six years after enactment of the CAA, approximately 70 million people live, in 108 counties, where air quality levels have exceeded the ozone standard (National Air Quality and Emissions Trends Report, 1995). Recent proposed changes to the current ozone NAAQS (USEPA, 1996) may impact even more urban areas.

Although past ozone control efforts have not fully succeeded, two decades experience attempting to reduce urban ozone has netted some significant achievements. Auto manufacturers have demonstrated that substantial emission reductions can be

[1] U.S.C. Section 7401 (b)(1)

[2] Ozone, sulfur dioxide, carbon dioxide, particulate matter, nitrogen dioxide, and lead

realized where once thought technically and economically unfeasible. Coupled with a much greater understanding of the principles surrounding ozone formation and transport, the 1990 CAA Amendments offer the promise that greater progress can be achieved.

To meet ozone air quality goals[3], it is clear that further reductions in ozone precursor emissions (nitrogen oxides, hydrocarbons, and carbon monoxide) are necessary. As policy analysts and public decision makers identify sources of additional emission reductions, a greater burden has been placed on emissions models in an attempt to evaluate the effectiveness of such measures. Current control strategy evaluation practices depend heavily on emission estimation methods developed in response to the 1970 CAA Amendments. These methodologies were designed to provide regional emission estimates, and do not provide the level of detail or certainty necessary to evaluate impacts of specific local control measures. Although stationary source emission estimation methods and available data yield fairly certain emission estimates, transportation related emission estimates are highly uncertain. In fact, research suggests that in 1990, models significantly under predict actual nitrogen oxide (NO_X) emissions from mobile sources by a factor of two or three (Pierson et al., 1990).

Both the USEPA and California Air Resources Board (CARB), as well as most other interested parties, recognize current mobile source modeling deficiencies. Several long-term efforts which employ new methods for estimating emission are currently

[3] National ambient air quality standards

underway[4], as are efforts attempting to improve upon existing estimation methods. However, these efforts primarily focus on improving estimation techniques for light-duty gasoline vehicles (LDGV). Heavy-duty diesel vehicle[5] (HDDV) emission estimates are far more uncertain and reducing emissions from these sources is becoming increasingly important.

Recently, reductions in NO_X have been identified as the most effective ozone control strategy in many areas of the country, including the Atlanta metropolitan region. As a result, many urban areas attempting to meet ozone standards are placing greater emphasis on reducing emissions from heavy-duty diesel engines. Due to the significant amount of uncertainty associated with "in-use" HDDV emission estimates, however, policy analysts can not effectively evaluate the impact of existing and proposed control measures.

HDDV emission estimates are normally developed by multiplying pollutant emission factors in grams per mile (g/mi) by vehicle miles traveled (VMT) activity estimates. Current HDDV emission factors (g/mi) were developed based on data generated from new engine dynamometer tests (in grams per brake horsepower hour[6]) performed by the manufacturer and a sampling of 13 "in-use" heavy-duty diesel engines (model year 1979/80) performed by the United States Environmental Protection Agency

[4] The new modeling approaches attempt to more accurately relate vehicle activity to emissions production through the use of either analytical functions (Barth et al., 1996; NCHRP model, University of California at Riverside) or statistically derived linear models (Washington, 1996; Geographic Information System (GIS) based model, Georgia Institute of Technology).
[5] For the purpose of this document, HDDV is used to identify diesel trucks greater than 33,000 lb gross vehicular weight rating (GVWR).

(USEPA) in 1984 (Guensler, 1994). How well these emissions represent actual "in-use" emissions is not well established, and the degree to which these results can be extrapolated across the entire fleet is highly uncertain.

Researchers have also questioned the accuracy of current HDDV estimates for "in-use" emissions deterioration (Guensler, 1994). Deterioration rates are necessary for predicting mobile source emissions because emissions increase with vehicle age and accumulated mileage. The need to verify "in-use" emissions deterioration will become increasingly important as more strict emission standards are enacted. Engine manufacturers will likely be required to introduce "add-on" technologies designed solely for the purpose of emissions control in order to meet proposed new engine certification standards[7]. Unlike light-duty gasoline engines, heavy-duty diesel engines can accumulate in excess of 600,000 miles before the first engine rebuild, and are often rebuilt many times over their useful life[8]. Expected emission reductions could be jeopardized by control equipment failure during the engine's life. Developing methods to evaluate the performance of heavy-duty engine emissions control equipment (similar to current light-duty inspection and maintenance programs), will become increasingly important.

The focus of this research is to evaluate methods used to estimate "in-use" HDDV emission factors. Compared to LDGV, very little "in-use" HDDV emissions

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[6] Brake horsepower hour is a unit of energy consumed at the wheels and does not include energy losses due to accessory loads (pumps, compressors, electronics, etc..).

[7] A goal to reduce NO_X emissions to levels at or near 2.0 g/bhp-hr beginning in 2004 has recently been established (USEPA, 1995).

data have been collected. Obtaining such data is important for the evaluation of HDDV emission factors generated based on current estimation methods, and as part of the development of new emission estimation modeling approaches (the GIS based model in particular).

Background

The development of modern day air quality legislation began in the 1950s and 1960s. Early air pollution legislation, including the Air Pollution Control Act of 1955 and the Motor Vehicle Act of 1960, provided for research and technical assistance to work toward a better understanding of the causes and effects of air pollution. Federal regulation began with the Clean Air Act of 1963 which required the Secretary of Health, Education, and Welfare to assist states in defining air quality criteria based on the scientific studies. The Motor Vehicle Air Pollution Control Act of 1965 represented Congress's first direct attempt at reducing air pollution by requiring automobiles to cut hydrocarbon and carbon monoxide emissions by approximately 50 percent by 1970. The final clean air law prior to 1970 was the Air Quality Act of 1967. This Act was much more comprehensive, and required states to establish ambient air quality standards consistent with federal criteria, as well as adopt implementation plans designed to meet the standards.

Although pre-1970 clean air legislation is very important from a historical perspective, these laws were primarily research oriented. This legislation and related

[8] In fact, many engines are designed with cylinder sleeves that can be readily replaced.

scientific findings were, however, used as resources in the development of air pollution regulation enacted in response to the 1970 CAA Amendments. Under the direction of the newly formed USEPA, this effort resulted in the passage of an unprecedented amount of environmental legislation during the mid 70's, and is responsible for much of today's regulatory infrastructure. Most significantly, the six criteria NAAQS were established[9], as were the methods designed to bring nonattainment areas back into compliance with these standards.

Central to the method developed for nonattainment area reclassification is the State Implementation Plan (SIP). SIPs are comprehensive documents prepared by states that describe how nonattainment areas will meet ambient air quality standards by a designated date. The SIP requires states to prepare emission inventories for stationary, mobile, and area sources for a base year and a target future year. Using models, the effectiveness of various control measures are gauged against the baseline and target[10] inventories and measures are adopted to ensure that the two converge by the designated date.

When the SIP process and associated emissions inventory estimation methods were developed, attainment deadlines were set in 1975 (Percival, 1992). Obviously the level of effort necessary to meet the NAAQS was severely underestimated, especially the standard for ozone. However, many of the emission estimation methods first developed

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[9] The CAA required the USEPA to establish NAAQS to protect human health and welfare through the scientific evaluation and public participation process.

[10] The target inventory is estimated using air quality models and represents the amount of pollutant emissions that can be released while still meeting the NAAQS.

in the mid 70s are still in practice today. Of primary concern are the models and associated methods used to predict emissions from transportation sources.

It is widely recognized that the current mobile source emission estimation methods do not meet present day ozone SIP planning needs. HC and NO_X emissions from mobile sources comprise a significant portion of most ozone nonattainment area emission inventories. However, as NO_X emissions have become increasingly important to the control of ozone, a greater emphasis has been placed on improving (or at least validating) NO_X emission estimates (National Research Council, 1991). The need exists because there was little motivation on a national level for creating an accurate NO_X emissions inventory at the time emission estimation methods were developed.

Although there is a primary NAAQS for nitrogen dioxide (NO_2), the attainment level is set sufficiently high so as to warrant little national concern[11]. The only geographical area to trigger NO_2 nonattainment requirements during the last decade is Los Angeles, California (USEPA, 1996). However, Los Angeles's air pollution problems are unique and substantially worse than the rest of the nation. Of the six criteria pollutants, NO_2 attainment was of the least concern; and in fact, no urban area has violated the Federal standard over the past five years (Air Quality Trends, 1995).

NO_X was recognized as an important contributor in the formation of ground-level ozone, however many of the mechanisms involved were not well established at the time. It was widely believed that the control of HC was the most effective strategy in reducing

[11] The NAAQS for NO_2 is 0.053 parts per million (ppm), annual arithmetic mean.

ozone. HC reductions were also less expensive (on a per ton basis) and more readily achievable than equivalent reductions in NO_X.

As part of the 1970 CAA Amendments, control measures were enacted that limited NO_X emissions from new and modified stationary sources, as well as motor vehicles[12]. However, such legislation was established merely to prevent growth in the NO_X emissions inventory while control measures targeting HC reductions were phased in (primarily in the form of motor vehicle emission controls). Instead of focusing on accurately quantifying how much NO_X was being emitted, the concern instead was ensuring that the amount did not increase.

Our understanding of the complex chemical reactions leading to the formation of ozone has increased significantly in recent years. It is now widely believed that the control of NO_X is the most effective strategy for reducing ozone in many areas of the country (National Research Council, 1991; Southern Oxidant Study, 1995). Regionally, high ozone episodes witnessed in the eastern half of the United States are NO_X limited primarily due to the significant amounts of biogenic HC emissions released in these areas. Anthropogenic HC reductions in urban nonattainment areas located in these regions will generally yield only minor reductions in ozone and will have less impact than comparable reductions in NO_X emissions.

[12] The original target was 0.4 g/mi by 1976, however in 1977, the enforcement was delayed until 1981 and relaxed to 1.0 g/mi.

The shift from a HC to NO_X control strategy in many areas has evolved over a period of several years. As interest in NO_X control has mounted, the need to developed better methods for estimating NO_X emissions has become increasingly apparent. Reconciling emissions estimates from stationary sources is comparatively easy, as most of these emissions are released from a relatively few sources. Virtually all of the large sources have had, or currently have, some type of emissions monitoring requirement.

The primary area for uncertainty in NO_X emission estimates can be attributed to motor vehicles[13]. Over the past several years a substantial amount of work seeking improvements in existing LDGV emission estimates has occurred and more is forthcoming[14]. A far greater amount of uncertainty, however, surrounds current heavy-duty vehicle estimation methodologies. Comparatively little effort has been placed on refining these methods because emissions from HDDV do not comprise a significant a portion of urban CO and HC inventories[15]. Now that reductions in NO_X have been identified as the most effective ozone control strategy in many areas of the country, HDDV NO_X reduction and emission estimation improvement efforts are receiving greater interest because emissions from these vehicles comprise a significant portion of urban NO_X inventories.

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[13] NO_X emission estimates from mobile sources are comparable in magnitude to NO_X emission estimates from stationary sources (National Air Quality and Emissions Trends Report, 1995).

[14]MOBILE (the USEPA's model for estimating mobile source emissions) has been reissued at least eight times, and another revision is scheduled to be released in 1998 (MOBILE6). Furthermore, a multi-year program attempting to re-evaluate the Federal Test Procedure[14] (FTP; 40CFR86 Subpart B) is also currently in progress

[15] Much of the interest in obtaining more accurate LDGV emission estimates has been motivated by CO and HC emission reduction efforts.

NO_X Emissions Inventory and Regulatory Trends

Although emission estimates from transportation related sources are highly uncertain, a comparison of recent estimates is useful to illustrate the importance of the HDDV emissions contribution. According to the USEPA, transportation sources[16] are responsible for roughly 50 percent of NO_X releases to the atmosphere (National Air Quality and Emissions Trends Report, 1995).

A breakdown of NO_X emissions by mobile source type and vehicle classification is provided in Table 1.1. The relative contributions presented in Table 1.1 are based on a heavy-duty vehicle classification of greater than 8,500 lb gross vehicular weight rating (GVWR). However, almost all heavy-duty vehicle NO_X emissions can be attributed to diesel powered trucks greater than 33,000 lb GVWR; mainly because HDDV are responsible for approximately 98 percent of all diesel truck VMT (Cambridge Systems Inc., 1995). Although HDDV represent less than 1 percent of highway vehicles (Transportation Energy Data Book, 1996), they account for approximately 20 percent of transportation related NO_X emissions, and approximately 10 percent of the national NO_X emissions inventory.

[16] Transportation sources are often classified as either light-duty highway, heavy-duty highway, or non-road.

Table 1.1 NO_X emissions from transportation sources; 1994[a]

Transportation category	Classification	Fuel type	Percent of total[b]
Non-road	Railroad		9%
	Other off-highway		20%
Highway	Light-duty	Gasoline	49%
		Diesel	<1%
	Heavy-duty	Gasoline	3%
		Diesel	19%

[a]Data adopted from the Transportation Data Energy Book, 16th Edition, 1996
[b]Percent of total transportation contribution
[c]Less than 8500 pounds GVWR

Based on current control measures, national NO_X emissions trends are projected to the year 2020 in Figure 1.1 (USEPA, 1995). Both mobile and stationary source components are presented. NO_X emissions are projected to decline slightly over the next few years as 1990 CAA Amendment control measures on stationary and mobile sources are phased in. However, a projected increase in mobile source activity suggests that the inventory will begin rising again at the turn of the century. As a result, emphasis has been placed on identifying sources of future emission reductions. Due to past regulation, most stationary sources and LDGV emit at only a fraction of their uncontrolled rates. Attempting to achieve further emission reductions from these sources will be increasingly expensive, and in some cases, not technically feasible.

Recognizing these difficulties, the USEPA has recently identified heavy-duty highway (USEPA, 1995) and non-road diesel engines (USEPA, 1997) as a major source for future NO_X emission reductions. Although prior restrictions have been placed on heavy-duty diesel engines, this is the first technology forcing standard to target non-road diesel engines.

Heavy-duty diesel engine manufacturers have developed new technical approaches in response to increasingly stringent emissions standards. Limits were first set at 16.0 grams of pollutant per brake horsepower hour (g/bhp-hr) in 1974, and have dropped to 5.0 g/bhp-hr for today's engines. These results, coupled with the identification of other new technologies and approaches suggest that substantial further reductions can be realized. As a result, the USEPA, CARB, and representatives of the heavy-duty engine manufacturing industry recently signed a Statement of Principles (SOP) in an effort to reduce NO_X emissions to levels at or near 2.0 g/bhp-hr beginning in 2004 (USEPA, 1995).

Emission Characteristics of Gasoline and Diesel Engines

The USEPA has not placed severe restrictions on diesel engine emissions because of technical difficulties inherent to diesel engine combustion (diesel cycle). While diesel engines are much more efficient than their gasoline counterparts, internal combustion principles governing the resultant greater efficiency also provide for high NO_X (and particulate matter) emissions.

The greater overall efficiency of diesel engines can be attributed to higher compression ratios and non-stoichiometric (lean) air-to-fuel mixtures. Unlike gasoline engines (Otto cycle), diesel engines do not require a spark to initiate combustion. The fuel and air mixture is compressed to very high pressures and combustion occurs when the mixture reaches the fuel compression-ignition temperature. Diesel engine compression ratios typically range 12:1 - 24:1 (Stone, 1992), while gasoline compression ratios range from 7:1 - 10:1 (Bosch, 1993).

The need to compress the fuel and air mixture to very high pressures results in high flame temperatures, which in turn promotes NO_X formation. In comparison to the Otto cycle, NO_X emissions from the diesel cycle are significantly greater due to the higher peak combustion temperatures and the ineffectiveness of the conventional exhaust gas catalyst systems used in gasoline fueled vehicles. Three-way catalyst systems are not effective under the fuel-lean operating conditions inherent to the diesel cycle[17]. Gasoline engines typically operate at or near stoichiometric air-to-fuel ratios (AFR, 14.7:1), while diesel engine AFR range from approximately 80:1 at idle to 18:1 at full load (Ganesan, 1996).

Conversely, high temperature and pressure and greater excess air results in significantly lower CO emissions from the diesel cycle. Higher oxygen concentrations promote the oxidation of CO to CO_2 in this environment.

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[17] The maximum NO_X removal efficiency for three-way catalyst systems occurs near stoichiometric operating conditions.

The amount of HC emitted from compression-ignition combustion is comparable to spark-ignition combustion, however, differences in fuel volatility greatly affects the amount of overall HC emissions for each engine type. Due to the low volatility of diesel fuel, evaporative emissions from diesel engines are very low (as are HC emissions associated with refueling practices).

Particulate matter (PM) emissions from motor vehicles are also of major concern. Particulate emissions are usually classified as either primary or secondary, where primary particulates are derived from tailpipe emissions and brake and tire wear, and secondary partiulates result from condensation or chemical reaction processes initiated by primary particulates, or from the resuspension of materials induced by vehicle activity. In general, HDDV emit significantly greater amounts of PM in comparison to LDGV[18]. The greater PM (smoke and condensed HC) emissions can be attributed to the higher combustion temperatures and poorer fuel/air mixing characteristic to diesel cycle combustion, as well as higher emissions due to increased brake and tire wear. For a detailed analysis of motor vehicle particulate emissions consult "Assessment of Highway Particulate Impacts: Impact Assessment, Mitigation, and Perspectives" prepared by E.H. Pechan & Associates, Inc. (1996).

Mobile Source Emission Estimates

[18] Results from studies performed in the Fort McHenry Tunnel indicate that HDDV PM emission rates are roughly 10 times greater than LDGV emission rates (Pechan & Associates, Inc., 1996).

Mobile source emissions are estimated by the product of an emissions-producing vehicle activity factor and an activity-specific emission rate. Emissions-producing vehicle activities are events or vehicle attributes that result in a release of pollutants (e.g. cars, trips, starts, miles traveled, etc..). Current methodologies attempt to quantify both the number and the amount of pollutants released, associated with each emissions-producing vehicle activity. Total emissions are estimated by summing resultant emissions from all vehicle activities.

Heavy-duty vehicle emissions estimation methods differ significantly from light-duty methods, and are far more uncertain. Currently, total VMT is the only activity parameter used to estimate heavy-duty emissions. Other light-duty vehicle activity predictors (number of vehicles, number of trips, hours of idling) are not used for estimating heavy-duty emissions for several reasons, including, lack of sufficient data sources for estimating activities, differences in emissions characteristics between gasoline and diesel fueled engines, and differences in operating modes and uses between light- and heavy-duty vehicles. The number heavy-duty vehicles is not used as an activity predictor primarily because many of the vehicles operating within the any urban region are registered in other counties or states. No reliable data source or method exists to estimate the number of trucks operating in an urban area.

Because heavy-duty vehicles are commonly used for commercial purposes, light-duty vehicle activity estimates for the number of trips (daily) are not practical for use in the estimation of emissions from heavy-duty vehicles. Number of trips is principally used to estimate evaporative emissions following the end of a trip and elevated vehicle emissions resulting from cold engine operations (cold start). Both evaporative and cold start emissions are much more significant for gasoline fueled vehicles[19]. The number of hours idling used to estimate light-duty vehicle emissions is also not used for heavy-vehicle emissions estimation purposes. The USEPA attempts to account for idling by including idling operations as part of the new engine dynamometer test cycle used to develop baseline heavy-duty emission factors (discussed in greater detail later in this chapter).

While most urban areas use output from Urban Transportation Planning System (UTPS)[20] models to estimate light-duty VMT, traffic counters operated for the Highway Performance Monitoring System (HPMS) are typically used to estimate heavy-duty VMT because UTPS models do not apply to commercial vehicles. As a result, major uncertainty exists in heavy-duty VMT estimates because HPMS data collection methods were not designed with this intent. Traffic counts are performed infrequently and at locations chosen for transportation planning purposes. Few permanent monitoring locations exist as part of the HPMS and the algorithms utilized to convert pressure actuated axle counts to VMT are problematic and inaccurate (Guensler, 1994).

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[19] Attempts have been made to account for emissions increases due to cold start operations. This activity is indirectly included as part of baseline emission factors and will be discussed in greater detail later in this chapter.

[20] The UTPS uses origin-destination surveys to generate trip data based on land-use and socioeconomic characteristics, and was originally developed (and still is operational) for use by local administrators to evaluate the impact of roadway and transit alternatives (U.S. Department of Transportation, 1980).

Significant differences also exist in the methods used to develop baseline emission factors. It is widely acknowledged that vehicle emissions factors should be developed based on emissions tests that incorporate transient engine speeds and loads representative of expected vehicle driving conditions. Light-duty vehicle emission factors (in g/mi) are developed based on results from chassis dynamometer[21] tests used to enforce new vehicle emissions standards (Federal Test Procedure, 40CFR86 Subpart B). The Federal Test Procedure (FTP) was designed to represent a transient drive cycle over a flat road. Although it is widely recognized that the FTP does not adequately capture emissions caused by high power and load conditions[22], interested parties are reasonably confident that cycles will be developed that can adequately predict "in-use" emissions based on chassis dynamometer test results.

On the other hand, heavy-duty vehicle emission factors (in g/bhp-hr) are developed based on engine dynamometer tests used to enforce new engine emissions standards[23] (40CFR86.1327-96). While much research has focused on developing light-duty vehicle test cycles that characterize actual driving behavior, the heavy-duty engine test procedure has received very little attention. These tests are performed by the manufacturer and involve measuring emissions as variable loads (idle, 2, 25, 50, 75, and

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[21] Chassis dynamometers allow the vehicle to be placed directly on the roller, therefore, power to be absorbed at the wheels to better simulate on-road driving conditions

[22] Findings from several studies have found that significant emissions can result from high power and load operating conditions (see Carlock, 1992, LeBlanc et al., 1994, Cicero-Fernandez et al., 1995).

[23] This type of standard enforcement practice was chosen because it would be extremely complex and burdensome to require heavy-duty vehicle manufacturers to perform chassis dynamometer testing. Issues regarding responsible parties would arise because most engines are supplied by third party manufacturers, and heavy-duty vehicles incorporate a wide range of engine/transmission combinations, also know to

100 percent of the observed maximum engine torque) are applied directly to the engine. In "real-world" applications, however, drivers would favor an engine speed[24] that provides for good gas mileage (or greatest overall efficiency). Although this speed may be represented within the test cycle (at or near one of the variable loads), the method is weighted such that the speed can only represent a maximum of 15 percent of the test cycle (40CFR86.1327-96). Furthermore, the test cycle includes 36 percent idle operation and weights emissions results based on 1/7 cold start[25] and 6/7 hot start operations (Guensler, 1994). Whether or not these operating modes represent actual vehicle operation is also highly unlikely.

Baseline Heavy-Duty Vehicle Emission Factors

As previously mentioned, current baseline HDDV emission factors were developed based on new engine dynamometer tests and a sampling of thirteen "in-use" engines (model year 1979/80) performed by the USEPA in 1984 (Guensler, 1994). Engine dynamometer test results, in units of g/bhp-hr, were converted to units of g/mi (using conversion factors), for the application of estimated VMT necessary to estimate pollutant emissions. Finally, deterioration factors were also applied to baseline emission factors in an attempt to account for changes in emissions due to increases in engine age and accrued mileage.

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significantly affect emission rates (Clark et al., 1995). Heavy-duty chassis dynamometers are also very expensive to own and operate.

[24] Engine speed is generally measured in revolutions per minute (RPM).

[25] Cold start results are determined by performing engine the certification test directly following initial engine start-up (hot start is analogous).

How well these emission factors represent actual "in-use" emissions is highly uncertain. The "in-use" engines that were tested may not be representative of (and do not represent a statistically significant sampling in comparison to) the approximately two million HDDV operating in the U.S. (Transportation Energy Data Book, 1996). Furthermore, conversion factor and deterioration rate estimates also developed based on this limited sampling (and a manufacturer survey and testing of new model year 1987 engines) introduce further uncertainty, as does the need to project these estimates for other model years.

The conversion factors required to transform units from g/bhp-hr to g/mi were developed by estimating the brake-specific fuel consumption (BSFC, pounds fuel/bhp-hr) and average fuel economy (miles/gallon) for each model year. Based on the variability of BSFC data collected during 1984 tests (range from 0.40 to 0.50 lb fuel/bhp-hr), some uncertainty must be associated with BSFC estimates. The fuel economy data used in developing conversion factors were based on the Census Bureau's 1982 Truck Inventory and Use Survey (TIUS). Vehicle fuel economy is strongly influenced by vehicle load and will vary significantly between rural and urban environments. Furthermore, fuel economy data represent the means by which real-world load requirements are incorporated into emissions estimates. By using fleet-average fuel economy data in developing conversion factors, one essentially assumes that vehicle emissions from highly variable load conditions can be approximated by those from a single load. Whether or not the average load predicted by the TIUS represents real-world activities is somewhat uncertain. Furthermore, fuel economy estimates for calendar years other than 1982 are projected based on assumed changes in vehicle drag coefficients, engine and transmission lubricants, radial tire technology, and vehicle weight requirements. These projections further increase the level of uncertainty.

Finally, engine deterioration rates were also developed based on data collected from the USEPA's (1984) testing of thirteen model year 1979/80 engines, and deterioration rate estimates for other model years have been projected based on this limited sampling. Today's engines utilize technologies and related components not available on 1979/80 engines and the impact of these technologies on engine deterioration rates has not been adequately evaluated.

Recent "In-Use" HDDV Emissions Research

How well emission factors developed based on engine dynamometer test results can predict "in-use" heavy-duty vehicle emissions is difficult to establish. It is both arduous and expensive to develop relationships between engine and chassis dynamometer test procedures because the process of removing an engine from an "in-use" vehicle is extremely expensive. As a result, attempts have been made to develop a transient heavy-duty chassis dynamometer test cycle which emulates the test cycle performed on new engines. Recent findings by Clark et al. (1995) suggest that the development of such a cycle may not be possible. Although comparable energy versus time traces between new engine and chassis tests were developed, a statistical analysis of the engine speeds between each test were distinctly different, and a significant portion of the speeds contained within the new engine dynamometer cycle "would not be favored by a competent driver" (Clark et al., 1995). Not only does this finding suggest that a comparison of new engine and chassis dynamometer test results may not be possible, but the finding also casts some doubt regarding whether or not the new engine dynamometer test cycle is representative of actual driving conditions.

Compared to light-duty vehicles, very little heavy-duty emissions data are available for comparison with current emission factor estimates. Several chassis dynamometers located in North America are capable of collecting "in-use" emissions data [26], however, emission factors developed using results from the new engine dynamometer test cycle can not be directly evaluated using chassis tests for the reasons stated above. Chassis dynamometers are most effective for evaluating the impact of control systems and alternative fuels and lubricants on vehicle emissions. Repetitive tests can be performed over the same test cycle, allowing for a direct evaluation of emission reduction potential.

Several studies have estimated "in-use" HDDV emission factors based on data collected in tunnels[27]. Although several have been successful, driving behavior in tunnels may not be representative of actual driving behavior. Furthermore, a direct

[26] Single roll chassis dynamometers are operated at the Southwest Research Institute in San Antonio, Texas, and the Southern California Rapid Transit District in Los Angeles , California. Twin roll dynamometers are in use at Environment Canada in Ottawa, Canada, Chevron Research and Technology Center in Richmond, California, and the Petroleum Research Facility in Mexico City, Mexico. A portable chassis dynamometer is also operated by the West Virginia Department of Mechanical Engineering in Morgantown, West Virginia.

evaluation of engine dynamometer based emission factors using tunnel study data is also not possible. Emission factors estimated from data collected in tunnels are reported in units of g/mi and reflect vehicle load and grade characteristics particular to the tunnel. Emission factors developed based on new engine dynamometer test results (g/bhp-hr) are converted to units of g/mi using conversion factors which include fleet-average fuel economy estimates, among other data. Fuel economy estimates embody vehicle load and grade characteristics that are probably significantly different from characteristics representative of the tunnel, thereby making a direct comparison of results difficult.

Instrumented truck studies now underway at the USEPA are attempting to develop "in-use" HDDV emission factors[28] (Acurex Environmental Corporation, 1995). An additional objective of this test program is to establish relationships between on-road emission factors and emissions collected using chassis and engine dynamometer test cycles. The on-road component of the test program uses a full-size trailer equipped with emissions instrumentation to test various tractors over a modal test matrix (varying speed, grade, load, and acceleration). On-road tests are also performed for a separate road course identified as the "certification cycle" for comparison with chassis and engine dynamometer tests.. Chassis tests are performed to establish agreement with urban driving cycles, modal cycles, and an adaptation of the "certification cycle." Following on-road and chassis test series, the engine is removed from the tractor and tested on an engine dynamometer also following an adapted "certification cycle."

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[27] The Fort McHenry Tunnel under Baltimore Harbor, the Tuscarora Mountain Tunnel of the Pennsylvania Turnpike, and the Cassiar Tunnel on the Trans-Canadian Highway near Vancouver, British Columbia.

Instrumented truck tests may represent the best approach currently available for developing "in-use" HDDV emission factors and establishing relationships between "in-use" emissions data with that collected using engine and chassis dynamometers. A significant drawback to this approach, however, is that the test program is very time consuming. The program was initiated in 1994 and to date, the test series has been completed for three tractors (Brown, 1997). Given the wide range of tractor sizes and configurations, researchers hope that other "in-use" measurement methods can be developed that might supplement the data collected as part of this program, and assist in the evaluation process.

Research Goals

Two methods which utilize ambient air measurements performed at a roadside location will be evaluated. As part, ambient air concentrations (NO_X, carbon monoxide, and carbon dioxide), meteorological parameters (wind speed, wind direction, and mixing height), and vehicle activity distributions (traffic counts, speed, and acceleration) will be monitored during nighttime hours. Based on the data collected, fleet-average HDDV NO_X emission factors will be developed and the results will be compared to new engine certification standards, as well as other emission factor data found in the literature. Furthermore, results from tests performed with a truck equipped with emissions instrumentation will be used to assess the reasonability of estimated emission factors and other parameters measured at the roadway test site.

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[28] The truck currently equipped with emissions instrumentation was also used as part of this study.

CHAPTER II

EXPERIMENTAL METHODS AND INSTRUMENTATION

This Chapter identifies the experimental methods and instrumentation used in this study. The general experimental approach is introduced along with a description of the sampling site and the attributes that led to its selection. Next, a description of the instruments used in the study is provided. This Chapter concludes with a description of tests performed at the site with an instrumented truck to assess the accuracy of developed emission factors.

Experimental Methods

The underlying principle motivating this study is that information related to surface emissions can be inferred from perturbations (i.e. deviations above background levels) in atmospheric concentrations of the species. For example, if one detects a pollutant in ambient air directly downwind of a source, one would infer that the source may have emitted the pollutant. However, if one were also to perform measurements directly upwind of the source and confirm that the pollutant was not present, then one could conclude that the source probably does emit the pollutant. This inference was directed from a measured atmospheric perturbation.

This principle has been used to obtain information related to source emissions. Remote sensing techniques utilize atmospheric perturbation observations to estimate vehicular emissions, as do chemical mass balance receptor models in assigning source apportionment. Heavy-duty diesel vehicle NO_X emission rates can, in principle, be estimated by observing how ambient concentration levels vary near a roadway. For the purpose of this study, two different methods are employed. The first method is a mass flux technique that correlates measured concentration gradients with traffic counts and meteorological parameters (wind speed and direction). The second method involves monitoring perturbations in ambient NO to CO_2 concentration ratios.

Mass Flux Technique

The chemical mass flux technique allows for the direct measurement of pollutant emission rates. This validated method (Hlavinka et al., 1988) has been successful in verifying line source air dispersion models on several occasions (Bullin et al., 1980; Zweidinger et al., 1988), however, several aspects specific to the mass flux technique used for this experiment.

In general, pollutant emission rates are calculated based on concentration profiles collected at upwind and downwind receptors. Receptors are arranged on opposite sides of the roadway (traditionally on towers). It is assumed that the difference in the amount of the pollutant flowing across upwind and downwind planes (as defined by receptor positioning) can be attributed to the vehicles traveling along the roadway.

Previous mass balance measurements performed by Bullin et al. (1980) were collected during unstable atmospheric conditions (i.e. daytime hours). A substantial amount of vertical mixing was expected, and as a result, several receptors were mounted at varying heights on towers. For the purpose of this experiment, testing was performed during nighttime hours in order to take advantage of the atmospheric inversion (as well as greater truck density). The presence of a stable atmosphere will significantly dampen the vertical concentration gradient by not allowing pollutants to penetrate the inversion layer. Then, if one assumes that the air mass very near the roadway is well-mixed, the average concentration along any vertical axis can be approximated by a single measurement. For this study, a height of 15 feet was chosen in an effort to place sample inlets level with a typical truck exhaust stack.

The experiment can be conceptualized through the use of Figure 2.1 which depicts a roadway directing traffic flow in one direction along the bottom of surface A is enclosed by a rectangular control volume. Traffic flows from west to east, perpendicular to planes E and W. Pollutant measurements are collected at the four locations along each edge of the rectangular control volume.

Given that the surface areas for opposite sides are roughly equal, the chemical mass balance equation for a non-reactive species[29] x is:

$$dm_x/dt = r_x + (C_{x,W} - C_{x,E})*A_{W,E}*u_x + (C_{x,N} - C_{x,S})*A_{N,S}*u_y + (C_{x,G} - C_{x,T})*A_{B,T}*u_z \quad (1)$$

where: m_x = mass of species x
r_x = rate of production of species x
$C_{x,I}$ = average pollutant concentration along plane I
A_I = surface area of plane I
$\underline{u}$ = three-dimensional wind speed vector

[29] The reactivity of CO is negligible over the small control volume used in this study.

Equation (1) can be simplified if one assumes that the flux entering across surface E will approximately equal the flux exiting across W. Furthermore, planes T and G are defined by the inversion layer and ground, respectively; assuming that the mass transfer across T and G is approximately zero, equation (1) can be simplified to give:

$$dm_x/dt = r_x + (C_{x,N} - C_{x,S})*l*h*u \sin(\Theta) \qquad (2)$$

where: l = average length between sampling points on north and south sides of roadway
h = inversion height
u sin(Θ) = wind component normal to roadway

By making several simplifying assumptions, Equation (2) now describes how the amount of pollutant x in the control volume changes with time. This system can approach steady-state provided that there exists a sustained wind normal to the road and a sufficiently long averaging interval is chosen. The averaging interval will be affected by changes in atmospheric stability, traffic volume, and fleet composition.

It should be noted that periods characterized by near steady-state conditions are not expected to be the norm. Meteorological conditions must be ideal and instrument malfunctions at a minimum for a successful data collection. By collecting data over a period consuming several nights, one seeks to increase the likelihood that a near steady-state event is encountered.

Provided that steady-state conditions prevail over a sufficiently long time period, the rate at which species x is produced (in g/sec) can be approximated as:

$$r_x = (C_{x,N} - C_{x,S})*l*h*u \sin(\Theta) \qquad (3)$$

A pollutant emissions rate (g/mi) is estimated by measuring vehicle counts and average speed over the selected averaging interval. Light-duty and heavy-duty contributions to the overall vehicle emission rate can be separated by performing an analysis of variance (ANOVA) between the combined vehicular emission rate and the observed fleet composition.

<u>NO/CO_2 Ratio Approach</u>

The NO/CO_2 ratio approach to estimating "in-use" HDDV NO_X emissions is similar to the LDGV emissions estimation technique employed by remote sensing (see Bishop et al., 1989). By observing how perturbations in NO and CO_2 change with time, NO_X emission factors are estimated using fleet-average fuel economy and fuel carbon content estimates. This approach is introduced most simply by example.

Trucks traveling along a roadway emit NO and CO_2, resulting in perturbations in local ambient concentrations[30]. Because they come from the same source, the relative concentration change NO to CO_2 is the same coming out of the exhaust stack as it is

[30] For the purpose of this study, NO_X emission factors will be developed based on NO measurements (discussed in more detail in Chapter IV).

measured at a roadside location. If one can accurately estimate the truck CO_2 emission rate, then the NO emission rate can also be estimated. The CO_2 emission rate can be reasonably estimated given the truck fuel economy and percent carbon and density of the fuel, assuming that all the fuel bound carbon is oxidized to CO_2.

A first analysis can be performed by assuming that the source of all measured CO_2 and NO is emitted by trucks. Provided that a majority of the vehicles are trucks, this is a reasonable assumption due to the fact that diesel trucks emit much more NO per gallon of fuel consumed than cars (Pierson et al., 1996). Also, vehicle fuel economy data indicates that heavy-duty trucks consume approximately 5 times the amount of fuel as light-duty vehicles on per mile basis.

However, emissions from light-duty and heavy-duty vehicles can be differentiated by data regression techniques as follows. For some time interval n, the emission rate for NO or CO_2 can be represented as a linear combination of light-duty and heavy-duty emission rates times their respective fleet composition:

$$ER_n = (1 - x_n) * L + x_n * H \quad (4)$$

Where: ER_n = vehicle emission rate over interval n
L = light-duty vehicle emission rate
H = heavy-duty vehicle emission rate
x_n = truck fleet composition

Equation (4) is not rigorously true because L and H are not truly constants. L and H will vary over different intervals due to changes in fleet compositions and influences of high-emitters. However, in principle, the undifferentiated emission rate relationship (4) is true over an extended averaging interval and has been demonstrated in several tunnel studies (Pierson et al., 1996; Wittorff et al. 1994).

This principle can be extend to the measurement approach utilized for the purpose of this study. From Equation (4), the ratio of NO to CO_2 can be represented as:

$$[NO]/[CO_2] = \{[\ (1-x_n)*L_{NO}] + x_n*H_{NO}\}\ /\ \{[(1-x_n)*L_{CO2}] + x_n*H_{CO2}\}*C \qquad (5)$$

where: L_{NO} = light-duty NO emission rate
H_{NO} = heavy-duty NO emission rate
L_{CO2} = light-duty CO_2 emission rate
H_{CO2} = heavy-duty CO_2 emission rate
C = conversion factor (molecular weight CO_2/molecular weight NO)

The observed $[NO]/[CO_2]$ ratio for light-duty and heavy-duty vehicles can be determined by performing a "least squares fit" of the observed ratio versus the fleet composition. The extremes of this regression analysis will yield the $[NO]/[CO_2]$ for light-duty and heavy-duty vehicle classes. That is:

$$[NO]/[CO_2] = \text{light-duty ratio at } x_n = 0 \qquad (6)$$

$$[NO]/[CO_2] = \text{heavy-duty ratio at } x_n = 1 \qquad (7)$$

NO_X emission rates for light-duty and heavy-duty vehicles are then estimated using fleet-average fuel economy data as mentioned previously.

Site Selection and Location

The sampling site selected for this experiment is located at Mile Post 6 along the west-bound lanes of U.S. Interstate 20, near Bremen, Georgia. This roadway location possessed several positive attributes that led to its selection.

To minimize the impact of lighter duty vehicle operation on roadside measurements, a roadway displaying a high truck fleet composition was sought. U.S. Interstate 20 between Atlanta, Georgia and Birmingham, Alabama is a major southeastern freight corridor. Therefore, a significant amount of heavy-duty truck traffic was expected. An initial survey performed on 5 February, 1996, and testing efforts conducted during the months of February, June, and October, 1996, demonstrated that truck fleet compositions in excess of 0.5 routinely occur during the night and can exceed 0.9 during early morning hours.

Another important site selection issue is road grade. Engine load affects vehicular emissions (emissions increase with load) and is strongly influenced by the road grade the vehicle encounters (Cicero-Fernandez, 1995). By selecting a roadway location where a limited uphill grade exists, one ensures that the engine is under load and operating at an efficient engine speed, as defined by the operator. The site selected is located near the top of an 2.5 percent grade, approximately one-half mile in length (Rikard, 1996). The topographical features of the site are presented in Figure 2.2.

Another aspect considered during the selection process was finding a location devoid of large stationary sources and other arterial roadways that might affect background concentrations. The site selected is in a rural area near the Georgia-Alabama border, 50 miles west of downtown Atlanta. The site also exhibits a large separation of approximately 400 feet between east- and west-bound roadways, thereby minimizing the impact of east-bound traffic on pollutant measurements.

Scale: 1 inch = 1,000 feet
20 foot contour interval

Figure 2.2 Roadway site topography; U.S. Interstate 20, near Bremen Georgia (adopted from U.S. Department of the Interior Geological Survey, Bremen Quadrangle, 1982)

Finally, a DOT salt and gravel storage facility was located adjacent to the roadway site. Associated with this facility was an access road linking east- and west-bound roadways. This access road and adjacent lot facilitated equipment deployment and provided a location to perform tethered balloon flights used to determine atmospheric inversion height.

Measurement Locations

The site was located in a heavily wooded area. A grass-covered area absent of trees extended approximately 40 feet from the roadway in either direction. The four roadway sampling locations (hereon referred to as Site 1, 2, etc..) are identified in Figure 2.3, as are the pollutant measurements performed at each location. Sampling equipment was housed in weatherproof, climate controlled enclosures at each location. A fiberglass enclosure housed equipment at Site 1, while cargo vans were utilized at Sites 2 and 4. Equipment at Site 3 was place in a recreational vehicle (RV).

Sites 1 and 3 each housed NO, CO, and CO_2 instruments and data logging equipment. A video camera was also located at Site 3 to record vehicle traffic activity. Wind speed and direction sensors were mounted on telescoping aluminum towers and erected adjacent to Sites 1 and 3. Site 1 and 2 sensors were placed at 13 and 10 meters, respectively. Sites 2 and 4 housed only NO instruments and instrument output was logged at Sites 1 and 3, respectively.

Three generators were required to power instrumentation and their locations are also identified in Figure 2.3. Sites 1 and 2 were powered by a 15kw propane generator located approximately 150 feet south of Site 1 along the access road. Propane fuel was housed in a 250 pound tank placed adjacent to the generator. Sites 3 and 4 were powered by gasoline generators contained within each site. A 6.0 kw generator was mounted in the rear of the RV (Site 3) and a 4.5 kw generator was placed within an enclosure near Site 4. Generator exhaust from Sites 3 and 4 were ducted in a manner so as to minimize interference. Ground-level observations at the site indicated that winds were generally in the direction of traffic flow (from east to west). Therefore, generator exhaust was ducted downhill (away from the roadway) and into the trees in a WNW direction, approximately 50 feet away from each site.

Ambient air was brought to the analyzers through 2 inch poly-vinyl-chloride (PVC) tubing forced by blowers[31]. Inlets were located 15 feet above ground and capped with rainhats to prevent water collection. Site 1 and 2 sample inlets were located directly adjacent to enclosures, however, Site 3 and 4 inlets were ducted an additional 50 feet east of the enclosures. Additional ducting was constructed in order to minimize generator interference. Teflon (PFA) tubing was used to direct sample air from the PVC duct to each analyzer. Tubing was connected to bulkhead fittings tapped into the PVC to prevent leakage.

[31] The residence time for the PVC/blower sampling system residence time was approximately 10 seconds for Sites 3 and 4, and approximately 2 seconds for Sites 1 and 2.

Tethered balloon flights were performed in a cleared area, approximately 150 feet in diameter, between the east- and west-bound roadways. A small gasoline generator was located at this area and was used to provide power for the wench, receiver, laptop, and spotting lights.

Vehicle speed and acceleration measurements were performed at a location approximately 500 feet east of Sites 2 and 3. This allowed for measurements to be performed on vehicles while passing through the site.

Instrumentation

A summary of instrument specifications is provided in Table 2.1. Chemilumenescent NO measurements were performed using TECO™ Model 42s analyzers. Non-dispersive infrared spectroscopy (NDIR) measurements for CO and CO_2 were performed using TECO Model 48 and LICOR™ Model LI-6262 analyzers, respectively. Tower wind speed and direction measurements were performed using

Table 2.1 Instrument specifications

Measurement parameter	Manufacture/ Model No.	Operating range	Accuracy	Response time
CO_2	LICOR/LI-6262	0-1000 ppm	$\pm$ 2 ppm	1 second
CO	TECO/48	0-10 ppm	$\pm$ 0.1 ppm	1 minute
NOx	TECO/42s	various	$\pm$ 1% of scale	1 minute
Wind speed	Climatronics/F460	0-50 m/s	$\pm$ 0.07 m/s	3 seconds
Wind direction	Climatronics/F460	0-360°	$\pm$ 2°	3 seconds

Climatronics sensor and data translator systems. Analyzer and tower sensor outputs were recorded using Labtech notebook ™ data acquisition software with 10 second averaging intervals.

Instrument calibrations were performed with EPA Protocol gases, utilizing gas dilution system. Mass flow meters in the dilution system were calibrated using an absolute positive displacement (soap bubble) flow meter. Flow dilution measurements were used to measure instrument calibration response. Because the TECO Model 48 CO analyzer experiences thermal drift, an analyzer zero check was performed at least twice daily. Zero checks were performed by passing ambient air through a palladium catalyst trap heated to 350 ^{o}C to remove ambient CO.

Tethered balloon meteorological measurements were performed using a Atmospheric Instrumentation Research Inc. (AIR) tethersonde ™ and 403 MHz receiver system. The flight system also included, a five cubic meter AIR tethered balloon controlled by an electric wench. The AIR tethersonde™ was mounted directly below the balloon and transmitted temperature, wind speed, wind direction, dew point, and elevation data to a receiver on the ground. Measurements were recorded every second and stored on a portable computer.

Vertical concentration profile measurements were performed using an ambient air collection device constructed by the Air Quality Lab at Georgia Tech (Georgia Department of Natural Resources, 1996). Light weight air sampling systems were attached to the wench line and placed at varying heights. Ambient air was collected in

Tedlar™ bags by Viton™ diaphragm pumps, using remote control identical to those found in model airplane systems. Such control provides for the simultaneous collection of air samples at three elevations.

A ProSurvey 1000 laser rangefinder was used to measure vehicle speed and acceleration parameters. The laser gun was operated at a maximum firing frequency providing range data at a rate of 238 hertz (Hz) and data was stored on a laptop computer prior to processing (Grant et al., 1996).

Instrumented Truck Tests

The operation of the instrumented truck used for this study was directed by the Emissions Modeling Branch (EMB) of the USEPA's Air Pollution Prevention and Control Division (APPCD). Actual measurements were performed by Acurex Environmental Corporation personnel. A 1990 Freightliner tractor powered by a Caterpillar 3176 engine was used for the tests. For the purpose of this study, a set of nine runs were performed at each of three different GVWR (28,220, 51,380, and 75,440 lb).

Instruments aboard the truck monitored real-time exhaust gas constituent emission rates, in addition to vehicle speed and acceleration. A continuous emissions monitoring system (CEMS) was used to measure and record exhaust gas pollutant concentrations of NO, CO, HC, and CO_2. Flow rates were monitored using differential pressure sensors and temperature sensors located in the truck exhaust stack. A frequency-to-voltage converter connected to the truck's tachometer was used to monitor engine speed. All instrument and sensor outputs were recorded on a unique Data Acquisition System (DAS) using one second averaging intervals.

NO_X emission rates generated from tests performed at the site with the instrumented truck will be used to access the accuracy of site specific NO_X emission factors developed based on ambient concentration levels measured at the Roadway site. In addition, other vehicle parameters collected as part of these tests will be used for data comparison purposes. Vehicle speed and acceleration data can be compared to fleet-average vehicle speed and acceleration measurements collected at the site. Also, instrumented truck fuel economy can be compared to fleet-average fuel economy data found in the literature, and engine load data can be compared to site specific truck road power estimates.

CHAPTER III

ROADWAY TEST RESULTS

This Chapter summarizes results from heavy-duty diesel roadway tests performed in 1996. Roadway measurements were performed on February 5, February 18 through 22, June 14 through 20, and October 1 through 11, 1996. All testing took place at the U.S. Interstate 20 site discussed in Chapter 2. The October effort was by far the most successful and represents the only instance where co-located NO and CO_2 instrumentation was operated on both sides of the roadway for an entire night. Data collected from efforts occurring in February and June are not reported because simultaneous data were not available. Measurement summaries for all test efforts are provided in Appendix B. A general description of the October test effort is provide below and a summary of October test results follows.

October, 1996 Tests

Photographs form the test site obtained during the October study are provided in Figures 3.1 through 3.3. Facing east, Figure 3.1 shows equipment located at Site 1 while Figure 3.2 provides a perspective of measurement Sites 3 and 4. Instruments located at Site 3 are shown in Figure 3.3. Typical site operation was as follows.

Generators were turned on and power was provided to instrumentation between 18:30 and 19:00 eastern standard time (EST) hours each evening. This allowed instrumentation to warm-up at least one hour prior to sunset. The video recorder used to monitor traffic activity was turned on at approximately 19:30 hours.

Tethered balloon flights were performed at two to three hour intervals during the night. Typically, the first flight was performed at 22:00 hours. A meteorological measurement-only flight was performed first to evaluate atmospheric stability and wind conditions. If winds were calm, air sampling systems were employed to collect ambient air samples at varying heights. Immediately following collection, the air samples were passed through the CO analyzer at Site 1 and bag CO concentrations were recorded.

Instrument calibrations were performed daily beginning at approximately 08:00 hours and ending at approximately 13:00 hours (instrument calibration results are provided in Appendix A). Sites 3 and 4 were shut down daily following instrument calibrations. Sites 1 and 2, powered by a 15kw generator, were shut down every other day.

Summary of Results

Results from the October measurements are summarized in Table 3.1. As previously mentioned, data are reported only for days where NO and CO_2 instrumentation was successfully operated on both sides of the roadway. Table 3.1 provides a summary of traffic activity and meteorological conditions, as well as ambient concentrations for each sampling location.

Traffic activity parameters include the percent of test period in which traffic activity was monitored, as well as the number of trucks and cars that passed through the sampling site during the video monitoring period (sometimes a subset of the total test period). An average fleet fraction, reported as trucks, is also provided and was calculated based on a five minute averaging interval.

Meteorological parameters reported include average wind direction and wind speed, and nominal inversion height. The standard deviation of wind speed (σ_{ws}) and direction (σ_{Θ}) observations are also provided. The reported wind data were collected at a Georgia Department of Natural Resources meteorological station located in Yorkville, Georgia, approximately 20 miles(32 kilometers) northeast of the site. Wind data presented in Table 3.1 provides a general description of local wind conditions (site specific wind data are discussed in Chapter 4).

NO, CO, and CO_2 measurement summaries are provided for each sampling location. A five minute averaging interval was used in determining minimum, maximum, and mean concentration data at each sampling location.

Vehicle speed and acceleration data collected are summarized in Table 3.2. Parameters listed include the number of trucks sampled, the time of day sampling was performed, and average truck speed. The median truck acceleration for all trucks sampled is 0.09 mph/s, while the ten and ninety percentile ranks are -1.07 mph/s and 1.50 mph/s, respectively. Although laser range finder measurements were also performed in October, the data were stored on a laptop computer which was stolen from the Institute before data could be downloaded. However, the consistency of readings between 1996 and 1997 gives high confidence in the stability of traffic patterns.

Table 3.2 Truck speed and acceleration results

Date	Time of day	Number of trucks sampled	Average speed (mph)
6/17/96	03:50	50	63.2
6/18/96	00:30	51	63.8
6/18/96	01:10	55	62.3
6/18/96	22:00	58	62.0
6/18/96	23:20	78	60.2
6/19/96	01:40	50	61.3
6/19/96	03:50	53	62.3
3/5/97	00:30	49	61.3
3/5/97	01:00	54	61.9
	Data Combined:	498	61.9

Data from October tests for the six nights reported (identified in Table 3.1) are summarized in Figures 3.4(a) through 3.4(r). The data presented were calculated using a five minute averaging interval. Vehicle activity (truck and car counts) and average NO concentration data are presented in Figure 3.4 (a), (d), (g), (j), (m), and (p). Reported average NO concentrations were calculated by averaging data collected at all sites. Sites 1 and 3 NO and CO_2 time series plots are presented in Figure 3.4 (b), (e), (h), (k), (n), and (q), and Figures 3.4 (c), (f), (i), (l), (o), and (r),respectively. Daily summaries describing events occurring on each particular night are provided in Appendix B.

Instrumented Truck Results Summary

A summary of instrumented truck tests performed at the roadway site are provided in Table 3.3. In general, triplicate tests were performed at three different target speeds for each load conditions (28,220, 51,380, and 75,440 lb GVWR), however, only two target speeds were tested at the full load (GVWR = 75, 440 lb) condition. Table 3.3 summarizes truck speed and acceleration, demanded power, fuel economy, and NO_X emission factors for all tests performed.

CHAPTER IV

DATA ANALYSIS AND DISCUSSION

This chapter summarizes data analysis efforts and results. First, influences affecting wind direction measurements collected at roadway sampling locations and their impact on the mass flux measurement technique are highlighted. Next, a description of the data analysis procedures leading to, and culminating in, the CO_2 fuel economy model are provided. This Chapter concludes with a comparison of NO_X emission factors developed as part of this study.

Mass Flux Method

Under favorable meteorological conditions, pollutant emission rates can be reasonably estimated by mass flux techniques (see Chapter 2). Requirements are stable atmospheric conditions accompanied by a sustained wind normal (or near normal) to the roadway.

Very low mixing heights were observed on several nights during this study. A vertical temperature profile for data collected on the night of October 8 is presented in Figure 4.1. A strong inversion is usually characterized by a greater than 1 °C temperature rise per 500 meters elevation gained. Data presented in Figure 4.1 represents an approximate rise of 1.5 °C in 25 meters, greatly exceeding this classification. Although other atmospheric inversions were generally not this severe, consistent mixing heights ranging from 18 to 30 meters were detected on most nights. Temperature profiles suggest that nighttime inversions were forming just above the tree canopy.

Based on Yorkville (Georgia Department of Natural Resources monitoring station located approximately 20 miles northeast of the Roadway test site) and tethered balloon measurements, sustained winds normal to the roadway were present during the October 4 and 11 tests. Winds were from the north-northeast on October 4 and from the north to northwest on October 11. Although some influence from winds above the tree canopy (assumed to be similar to Yorkville wind observations) was detected at Site 1 and 3 wind sensor locations, other competing influences affected the data.

The Site 3 wind direction sensor was placed at a height of 32 feet, well below the top of the tree canopy. In most cases, this sensor detected winds from the east, or with traffic flow. This occurred even when sonde and Yorkville wind data indicated that winds were not parallel to the roadway. This is consistent with recent findings by Carr et al. (1996), which showed that air near the roadway is dragged along in the direction of the moving vehicles. Because most vehicles involved in the Carr et al. study were automobiles, one would expect that this affect would be even more exaggerated for heavy-duty tractor trailers.

Wind direction data collected at Site 1 indicate that a combination of both actual (or above tree canopy) and traffic induced influences were detected. This sensor was placed approximately 20 feet below the top of the tree canopy, at a height of 40 feet. Data presented in Figure 4.2 provides a comparison of Site 1 and Yorkville wind data for measurements performed on 10-11 October. Also presented are average NO concentration data collected on the north (only Site 3) and south (Sites 1 and 2 averaged) sides of the roadway. As would be expected, south side NO levels are generally higher than north side levels (given northerly winds), however, a sustained wind normal to the roadway was not observed at the site.

In addition to site topography affecting wind measurements, mass flux measurements may have also been affected by the failure of any one of the assumptions identified in Chapter 2. The assumption that the air mass very near the roadway is well-mixed, allowing for representative sampling at a single point in the vertical plane, may not be appropriate. Vertical mixing near a roadway during stable atmospheric conditions is very complex and not well understood. Furthermore, vertical mixing may have been complicated further by the topographical differences between sites on the north and south side of the roadway (discussed in the proceeding sections).

NO/CO_2 Ratios Method

As discussed in Chapter 3, the NO/CO_2 ratios method uses perturbations in ambient NO and CO_2 concentrations levels measured near the roadway to estimate source emissions. NO and CO_2 measurements collected between midnight and 6 am at Sites 1 and 3 were used in this analysis. This interval was chosen to minimize the influence of LDGV emissions. Truck and car traffic counts and fleet composition data (based on a five minute averaging interval) collected over this test period are summarized in Table 4.1. Approximately 5500 trucks passed through the sampling site during the selected test intervals.

A one minute averaging interval for NO and CO_2 measurements was used in this analysis. Co-located 10 second NO and CO_2 measurements were time adjusted prior to creating one minute data averages to account for differences in NO and CO_2 instrument response times. In most cases, 10 second NO measurements were shifted forward 20 seconds with respect to CO_2 measurements.

Table 4.1 Vehicle activity totals; 00:00-06:00 hours

Test Date	Trucks	Cars	Average[a] fleet composition
4 October[b]	947	418	0.70
5 October[c]	684	566	0.56
7 October	677	542	0.57
9 October	1121	279	0.81
10 October	1043	507	0.72
11 October	949	759	0.61

[a]reported as trucks based on a five minute averaging interval
[b]missing 30 minutes of data
[c]totals from 00:00-05:00 hours

The initial step in data analysis was to evaluate the dependence of ambient NO and CO concentration levels on traffic activity (truck and car counts). Significant correlation was detected between NO concentration levels and truck counts, and CO concentration levels and car counts, while little to no correlation was detected between NO concentration levels and car counts, and CO concentration levels and truck counts. As can be expected, concentration data dependence on traffic activity was strongly influenced by the averaging interval chosen.

Average NO concentration (all sites averaged) and truck activity (number of trucks passing through the site) data are present in Figures 4.3(a) and 4.3(b) for testing performed during the morning of 10 October. Time series data presented in Figure 4.3(a) include NO concentrations reported using one minute averages and number of trucks passing through the site during a one minute interval. Similar data presented in Figure 4.3(b) illustrate how correlations can be improved by trial and error methods using low-pass data filtering techniques. The linear regression correlation coefficient (R^2) was improved from 0.17 to 0.34 in this case by using a four minute rolling average for NO concentration data and an eleven minute rolling average for truck activity.

Positive and significant correlations were also detected between NO concentration and truck counts data collected on other nights. R^2 coefficients for data collected on 7 October and 11 October are 0.51 and 0.43, respectively. A five minute rolling average was used for both data sets on these nights.

A similar dependence was also found between CO concentration data and car activity. For data collected on 7 October, an R^2 coefficient of 0.32 was determined using a one minute averaging interval. On the other had, little or no relationship could be established between CO concentration data and truck counts (0.002), and NO concentration data and car counts (0.03) for data collected on this night. Although the dependence of ambient concentration levels on traffic activity was not analyzed for all data sets, it is suspected that similar relationships could be established for each night testing was performed.

To estimate NO emissions from trucks based on ambient CO_2 concentration levels, a strong correlation must exist between these parameters. Two cases depicting a strong linear relationship between NO and CO_2 are provided in Figures 4.4 and 4.5. Data presented in Figure 4.4 were collected at Site 3 on October 9. Average Site 1 and 3 data collected on October 7 are presented in Figure 4.5. These plots indicate that a linear relationship exists for nights where ambient NO and CO_2 concentration levels are significantly different (October 9 concentration levels are approximately 4 times greater than October 7 levels).

A summary of all correlation coefficients is provided in Table 4.2. Two R^2 coefficients are provided for each sampling location on October 9 because a shift (of approximately 20 ppm) in background CO_2 concentrations occurred during the night. The R^2 coefficients were developed based on observations before and after the background shift occurred. Because the shift affected Site 1 and 3 measurements at different times, the Site 1 and 3 average data analysis does not include data collected from 03:14 to 03:49 hours (EST).

Table 4.2 Summary of R^2 coefficients from NO/CO_2 regression analysis

Test Date	Site 1	Site 3	Sites 1 and 3
4 October	0.73	0.59	0.69
5 October	0.21	0.41	0.59
7 October	0.37	0.83	0.77
9 October	0.77	0.89	0.83
10 October	0.61/0.45	0.54/0.55	0.61/0.37
11 October	0.58	0.47	0.36

In order to build a linear model to predict NO_X concentrations based on CO_2 measurements, background levels of NO and CO_2 must be estimated. In rural areas in the Southeast (as characterized by this sampling location), background NO concentrations less than 1 ppb are expected (Wang, 1992). For CO_2, a constant background concentration was estimated for each night by determining the intercept from the NO and CO_2 linear regression analysis. However, this analysis resulted in instances where estimated background CO_2 concentrations were greater than observed CO_2 concentration levels.

The need to determine background CO_2 concentration levels is avoided by considering how differential changes in CO_2 levels correlate with differential changes in NO levels. Given n observations, the differential change (hereafter referred to as dNO and dCO_2) of NO and CO_2 concentrations were calculated by subtracting the i^{th} observation from the i^{th}- 1 observation, for all cases. Figure 4.6 illustrates the strong linear relationship observed between dNO and dCO_2 concentration measurements performed at Site 3 on October 7.

A summary of dNO/dCO_2 model R^2 coefficients and slopes are provided in Table 4.3. Reported totals were determined by combining all data, however, data collected at Site 1 on October 5 and 7 were not included in developing combined totals for Site 1. Relatively low concentration levels detected at Site 1 on these nights resulted in the low R^2 coefficients listed in Table 4.3. As would be expected, general goodness of fit characteristics for dNO/dCO_2 and NO/CO_2 models are similar.

Table 4.3 Summary of R^2 coefficients from dNO/dCO_2 regression analysis

	Site 1		Site 3		Sites 1 and 3	
Test Date	R^2	slope	R^2	slope	R^2	slope
4 October	0.58	0.0081	0.69	0.011	0.69	0.011
5 October	0.29	0.0053	0.76	0.012	0.63	0.010
7 October	0.17	0.0035	0.77	0.012	0.65	0.011
9 October	0.69	0.0090	0.71	0.012	0.70	0.011
10 October	0.67	0.0085	0.59	0.011	0.68	0.0092
11 October	0.42	0.0088	0.52	0.012	0.54	0.011
All data:	0.42	0.0086	0.70	0.012	0.68	0.010

Further analysis was performed in an attempt to differentiate heavy-duty verses light-duty emission contributions. Ratios of NO/CO_2 were plotted versus fleet composition using one minute averages over the test periods indicated in Table 3.1 (generally 20:00 through 08:00 hours, see Chapter 3). Although this method has been successful in differentiating emission contributions in tunnels, this analysis yielded statistically insignificant results.

It was also necessary to determine background CO_2 concentrations as part of this analysis. As previously mentioned, NO versus CO_2 relationships indicate that background CO_2 levels are not constant. Therefore, further attempts were made to estimate how background CO_2 concentrations change in time. Rolling regression techniques were employed using 15, 30, and 60 minute data sets. A resultant intercept (or background CO_2 level) was computed for each one minute observation and a polynomial curve was fitted in an attempt to model how these levels varied in time. A rolling regression interval that best fit general CO_2 concentration trends was selected. Although much effort was placed in obtaining a best fit, estimated background CO_2 levels were somewhat uncertain and may have impacted this analysis.

Based on previous findings reported by Pierson et al (1996), NO/CO_2 ratios from HDDV are approximately 4 times greater than LDGV NO/CO_2 ratios (0.02 for HDDV and 0.005 for LDGV). Such findings suggest that this analysis should work given a wide range of fleet compositions and sufficiently high traffic volumes. Although HDDV traffic volume was high during Roadway data collection, fleet composition was fairly constant because testing was performed at night. As a result, some difficulty was encountered in selecting sufficiently long averaging intervals, while also allowing for some variability in fleet composition.

Finally, residuals from the dNO/dCO_2 analysis were plotted against time, truck counts, car counts, and CO concentration levels in an attempt to explain residual variance. A typical standardized residual plot is presented in Figure 4.7 for Site 1 car counts on the night of October 4. Residual plots were generated for four of the six nights tested and all plots indicated that the unexplained variance was random.

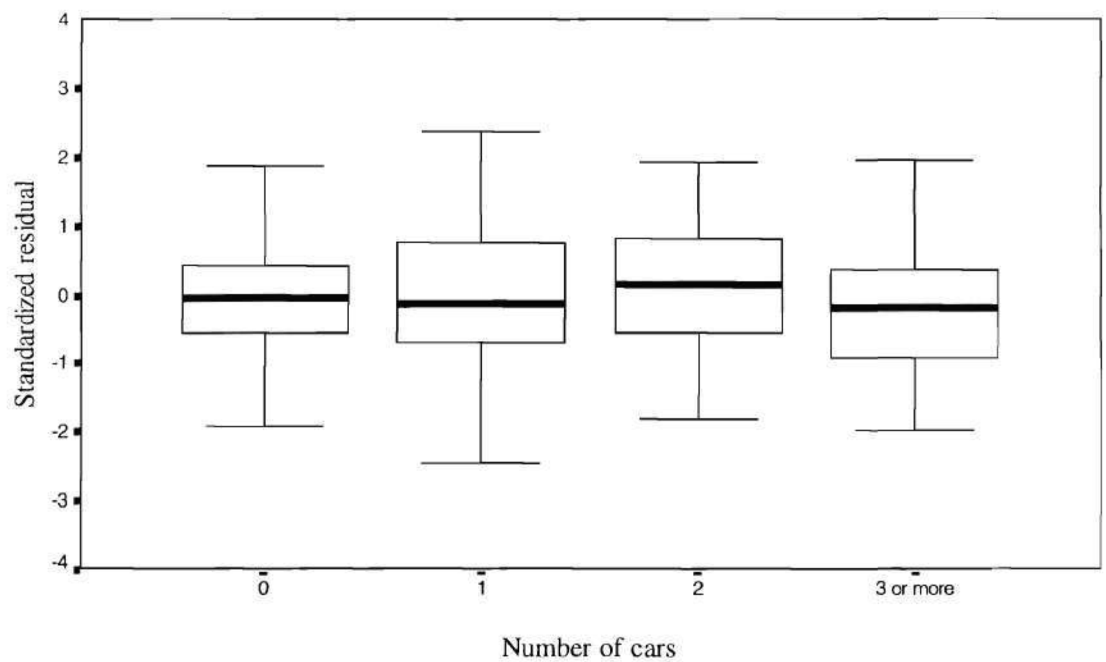

Figure 4.7 dNO/dCO2 residual plot against car counts; 4 October, Site 3

Results Comparison

Site 1 data regression slopes presented in Table 4.3 are consistently lower than similar values calculated for Site 3. In general, the test data suggests that better mixing characterized the Site 1 sampling location. Yorkville and tethered balloon wind direction data indicate that southerly winds were not detected on the nights tested. However, Site 1 (at no time upwind) mean NO_X concentration levels are generally lower than Site 3, even on occasions where winds were from the NNW.

Nevertheless, even if better mixing did occur at Site 1, relative NO/CO_2 ratios should be the same on both sides of the roadway provided that background concentration levels are the same. However, it is suspected that emission sources south of Site 1 (east-bound traffic and the generator located approximately 150 ft up the access road) may have affected background concentrations at this site. Even though wind direction sensors did not detect sustained winds from the south, turbulent flow patterns that typify a stable boundary layer may have resulted in northerly air flow between the roadways. As mentioned by Stull (1988):

> Stable boundary layer winds can have very complex characteristics. In the lowest 2 to 10 meters, cold air will drain down hill. Wind direction in this layer is determined by local topography; wind speed is governed by buoyancy, friction, and entrainment.

The roadway site is situated on a hill such that east-bound lanes are at a greater elevation with respect to west-bound lanes (were testing was performed). This downslope flow adjacent to Site 1 may have been enhanced by the access road connecting east- and west-bound roadways. The clearing would provide less friction and act to channel more dense air downhill. An additional influence is west-bound traffic activity. As previously mentioned, , Site 1 and 3 wind direction measurements indicate that air near the roadway was dragged along in the direction of traffic. This entrainment would further induce downslope flow adjacent to Site 1.

Background interference from emission sources south of Site 1 could lower the measured NO/CO_2 ratio (at Site 1) in several ways. First, vehicles traveling east-bound are moving downhill and a slightly lower NO/CO_2 might be expected (Pierson et al., 1996). As the air parcels migrate downhill, mixing will occur and some NO may be oxidized by ozone to form NO_2 (only NO measurements were performed). Emissions from the propane fueled generator located on the access road connecting the two roadways may have also interfered with Site 1 measurements. Compared to diesel and gasoline fueled vehicles, substantially lower NO/CO_2 ratios can be expected from the combustion of propane fuel.

Balloons filled with helium gas (pie balls) were used to observe flow conditions along the access road and near Site 1 on the night of March 4, 1997. Clear skies and stable conditions similar to those experienced during October tests occurred on this night. Balloon observations indicated that downslope flow moving directly from the generator location toward Site 1 was occurring, and the wind speed in the area was approximately 1 foot per second.

Based on the dNO/dCO for data collected at Site 3, NO_X emission factors reported in units of g/bhp-hr, g/mi, and g/hr are summarized in Table 4.4. The emission factors were calculated using a diesel fuel empirical formula of $C_{10.8}H_{18.7}$ (Turns, 1996) and an average fuel density of 0.773 g/cm^3 (Pierson et al., 1996). NO_X emission factors (EF) were calculated as follows:

$$EF_{(g/bhp\text{-}hr)} = R*F_{diesel}*BSFC \quad (1)$$
$$EF_{(g/hr)} = R*F_{diesel}*BSFC*DP \quad (2)$$
$$EF_{(g/mi)} = R*F_{diesel}*BSFC*DP*V \quad (3)$$

Where: R = slope from dNO/dCO_2 regression analysis
F_{diesel} = diesel fuel properties identified above
BSFC = assumed fleet-average BSFC
DP = site specific demanded horsepower estimate (see Appendix C discussion)
V = average speed of trucks passing through the sampling site (61.9 mph based on laser gun measurements)

Table 4.4 Site specific NO_X emission factor results summary[a]

Test Date	NO_X g/bhp-hr	NO_X g/hr	NO_X g/mi
4 October	6.28 ± 0.22	2010 ± 70	32.4 ± 1.1
5 October	6.62 ± 0.19	2120 ± 60	34.2 ± 1.0
7 October	6.73 ± 0.19	2150 ± 60	34.8 ± 1.0
9 October	6.85 ± 0.24	2190 ± 80	35.3 ± 1.3
10 October	6.12 ± 0.26	1960 ± 80	31.6 ± 1.4
11 October	6.56 ± 0.29	2100 ± 90	33.9 ± 1.5
All data:	6.51 ± 0.10	2080 ± 30	33.6 ± 0.5

[a]standard error limits do not contain uncertainty introduced by BSFC estimates

The assumed BSFC estimate was adopted from Cambridge Systematics, Inc., interim report Air Quality Issues in Intercity Freight (Cambridge Systematics Inc., 1995). Fleet-average BSFC data presented by Cambridge Systematics Inc. were developed from actual data collected up to model year 1987 (P. Machiele, "Heavy Duty Vehicle Emission Conversion Factors II 1962-2000," U.S. EPA, October 1988.). Data for future years were extrapolated by assuming an improvement of 0.01 lb/bhp-hr every three years. This rate of improvement is slightly less than that observed for model years 1976 through 1987. Projected BSCF rates for model years 1990 through 1996 ranges from 0.38 to 0.36 lb/bhp-hr. Data presented in Table 4.4 reflect an assumed fleet-average BSFC rate of 0.37 lb/bhp-hr.

Fleet-average NO_X emission factors (in g/bhp-hr) summarized in Table 4.4 are reasonable in comparison to past and present heavy-duty engine emissions standards. The federal NO_X emissions standard for model years 1994 and later is 5.0 g/bph-hr (CFR Part 86.094-11), while the standard for model years 1988 through 1993 was 10.7 g/bhp-hr (CFR Part 86.008-11). Although vehicle registration data was not collected as part of this effort, a fleet-average NO_X emission factor of 6.51 g/bhp-hr (all data averaged) is reasonable based on the emission standards and compliance dates.

Instrumented truck NO_X emission factors (see Table 3.3) also compare favorably to the site specific emission factors present in Table 4.4 (calculated based on the assumed site specific demanded power estimate of 320 bhp, see Appendix C). At half load (slightly less than the 57,400 lb GVWR measured on U.S. Interstate 20 near the test site), instrumented truck NO_X emission factors of 1960 g/hr and 32.6 g/mi were measured at an average truck speed of 60.2 mph (the average of three test runs). NO_X emission factors based on ambient air measurements performed at Site 3 (all data averaged) were 2080 g/hr and 33.6 g/mi at an average truck speed of 61.9 mph.

A comparison of the NO_X emission factor estimated based on roadway test data with findings reported for tests performed in tunnels is provided in Table 4.5. All emission factors are reported in units of g/mi. NO_X emission factor are reported for testing performed in 1992 at the Tuscarora Mountain Tunnel of the Pennsylvania Turnpike (Pierson et al., 1996). The Tuscarora Tunnel results were estimated based on measurement performed over a relatively flat grade. Findings from tests performed in 1996 at the Cassiar Tunnel in Vancouver, British Columbia (B.C.) also reported NO_X emission factors for variable grades ranging from +1.7 percent to -1.3 percent (Wittorff et al., 1994). Results for the Fort McHenry Study (performed in 1992) are reported for

Table 4.5 NO_X emission factor comparison with tunnel study findings

Test location	Road grade (percent)	NO_X emission factor (g/mi)
This study	+ 2.5	33.6 ± 0.5
Fort McHenry Tunnel	+ 3.3	22.5 ± 1.0
Fort McHenry Tunnel	- 1.8	9.7 ± 0.2
Tuscarora Tunnel	relatively flat	19.5 ± 0.9
Cassiar Tunnel	variable	17.3 ± 6.7

uphill and downhill grades of 3.3 percent and 1.8 percent, respectively (Pierson et al., 1996), and are low in comparison to NO_X emission factor developed based roadway tests. Results from the Fort McHenry Study could be biased low, however, due to experimental design limitations.

The Fort McHenry Tunnel runs underneath the Baltimore Harbor and consists of both uphill and downhill sections. Testing was performed in two bores where traffic flows west to east and ventilation air enters through the west portal and through two ventilation points inside the tunnel; all air exits through the east portal. Measurements were performed at all air inlet and exhaust locations, and at a mid-tunnel location near the bottom of the downhill grade affording the estimation of both downhill and uphill emission rates. By essentially dividing each bore into two tunnels, researchers dramatically increased the amount of potential experimental error for uphill grade emission rate estimates. As recognized by the researchers, "The overall sampling error in an experiment of this type should be ≅ 15%, but in the case of the uphill rates the error is much larger because the already polluted midtunnel air is the "entrance portal" of the uphill tunnel" (Pierson et al., 1996). Compounding the uncertainty, research also identified that cross-contamination between the two separate bores may have also occurred, affecting emission rate estimates by as much as 10 percent. Because LDGV were the primary vehicle using the other bore, cross-contamination would act to lower estimated heavy-duty emission rates. Finally, tracer gas studies were also performed as part of the Fort McHenry Tunnel study, however, results were not provided. The absence of these data precludes eliminating the possibility of problems associated with cross-contamination or air flow closure.

CHAPTER V

CONCLUSIONS, IMPLICATIONS, AND FUTURE RESEARCH

Conclusions

The ambient air techniques presented herein represent alternative methods for evaluating fleet-average HDDV emission factors for specific modes of operation. In comparison to studies performed in tunnels, roadside techniques provide for far greater flexibility in the types of operating conditions[32] (and roadways) that might be tested. Furthermore, these techniques also allow for the testing of an enormous number of vehicles. Based on June, 1996 roadway tests, emissions from approximately 5,500 trucks were measured during six nights of testing (36 hour test period). This represents a large fraction of available "in-use" emissions data.

Although some difficulty[33] was encountered in completing this test program, increasing success should accompany future roadway studies as a result of information gathered as part of this effort. The complex flow characteristics detected near the roadway were a result of the stable atmospheric conditions during which testing was performed, and were probably magnified by traffic flow and local topography. The

[32] Different speed and acceleration distributions, affects of grade, etc..
[33] Primarily problems associated with uncontrollable environmental conditions and demanding power requirements.

presence of turbulent flow greatly impacted mass flux measurements, and was probably the single greatest factor affecting the ability to evaluate emission factors using this technique.

The evaluation of HDDV NO_X emission factors using the NO/CO_2 ratio method, on the other hand, was successful. The emission factors developed using this model (and presented in Chapter IV) are reasonable in comparison to current heavy-duty engine emission standards as well as site specific emission factors developed based on instrumented truck measurements. Although it is difficult to accurately quantify overall uncertainty limits for roadway emission factors, it is doubtful that estimates are in error by an order of magnitude or greater. Therefore, roadway data suggests that current MOBILE5a heavy-duty emission factors (principally developed based on new engine certification test results) are reasonably accurate, and are probably not underestimated by a factor of two or three times, as suggested by Pierson et al. (1990).

Finally, of particular note is the degree to which energy based emission factors (in g/bhp-hr), multiplied by site-specific demanded horsepower, agreed with instrumented truck modal emission rates (in g/hr or g/mi). This finding suggests that heavy-duty NO_X emission rates may be accurately estimated using engine dynamometer test results (in g/bhp-hr) and demanded power estimates (in bhp), at least for high load, high speed, modes of operation.

Implications

Although current large heavy-duty vehicle emission factor estimates appear reasonable, more strict emission standards may have a substantial impact on the accuracy of future estimates. Compliance with past and present heavy-duty engine emission standards has been achieved, for the most part, by modifying the compression-ignition combustion process. An increase in light-duty deterioration rates due to add-on emission control system failure significantly increased uncertainties in light-duty vehicle emission estimates. It is also suspected that heavy-duty engine deterioration rates (or control system failure) will become increasingly important as more strict emission standards are imposed. Meeting such standards will required manufacturers to incorporate new engine technologies (including add-on emission controls), and the likelihood that such technologies will degrade or ultimately fail will increase. Therefore, the development of "in-use" heavy-duty vehicle emission estimation techniques is imperative if one hopes to improve upon, or at least maintain, the current level of uncertainty.

Roadway data indicate that demanded power can link engine dynamometer emission factors to "real-world" vehicle emission rates. This finding is extremely important from a heavy-duty emissions modeling perspective. Because most heavy-duty engines are supplied by third party manufacturers and there exists a wide range of engine/transmission combinations, engine dynamometer certification procedures represent the most cost-effective means of enforcing emission standards[34]. Much of the uncertainty[35] in current heavy-duty emission estimates stem from the need to relate emission factors developed based on engine dynamometer tests to vehicle activity estimates (VMT for heavy-duty vehicles). Roadway data suggest that demanded power may be a better predictor variable of heavy-duty emissions, and if such a relationship can be established, similar relationships should also follow for other heavy-duty engine pollutants.

A demanded power predictor variable would fit well within the framework of a modal emissions model, similar to the GIS based model currently under development at Georgia Tech (in cooperation with the USEPA). Unlike conventional models (MOBILE5a, EMFAC7G), a modal model provides for proper accounting of emissions from high power and load operating conditions (known to produce significant emissions) by disaggregating vehicle activity into modes of operation such as acceleration, deceleration, idle, and steady-state cruise.

Because activity patterns and emission rates for heavy-duty vehicles are significantly different in comparison to light-duty vehicles, the Georgia Tech/USEPA modal model development strategy is to estimate heavy-duty emissions within a separate emissions and activity module. Current plans are to integrate existing MOBILE5a

[34] Although manufactures can afford chassis dynamometers, the application of chassis dynamometer based emission standards for heavy-duty vehicles would be very difficult as a result of third party manufacturers and multiple engine/transmission configurations.

[35] The accuracy of VMT estimates are also highly uncertain (see Chapter I discussion regarding current mobile source emission estimation methods).

default emission rates directly into the module while modal emission rates are developed. If demanded power was used as the activity predictor, modal emission rates could be estimated by multiplying g/bhp-hr emission factors (based on vehicle classification) and demand power estimates on a segment basis for each link in the transportation network. This would significantly reduce the amount of data required to construct and maintain the emissions module by removing the need to develop on-road emission rates (g/s) for a variety of vehicle operating and load conditions.

Future Research

Recommendations for future research are provided in two sections. First, experimental design considerations are provided for both mass flux and NO/CO_2 ratio measurement techniques. These recommendations are provided for future roadway studies in an attempt to improve upon the data quality and overall success of each measurement technique. Second, further investigations and additional data needs are identified. These recommendations are provided to assist in the evaluation of HDDV emission factors and the development of improved emission estimation methodologies.

Experimental Design Considerations

In selecting future roadway test locations, the impact of local topography on mixing near the roadway should be evaluated. Downslope flow appears to have significantly impacted some roadway measurements performed as part of this study. Because plans are to continue to test on roads exhibiting uphill grades, potential interference from other emission sources resulting from downslope flow should be considered.

Better characterization of the complex flow patterns occurring near the roadway are necessary if mass flux measurement techniques are to be successful. Improved wind speed and direction measurements can be obtained using either a boundary layer wind profiler or sonic anemometer. Either instrument can also continuously monitor the height of the inversion layer, thereby removing the need to perform tethered balloon measurements[36].

Future flux measurement efforts should also evaluate vertical mixing assumptions[37] used for this study by measuring pollutant concentration levels at more than one sampling height. These data could be used to access whether or not the sample height chosen is representative of the average concentration in the vertical plane.

Improvements in NO/CO_2 ratios method data quality could be achieved by taking steps to increase the resolution in NOx instrument response. Due to electronic configurations established by the manufacturer, the TECO 42S NO_X analyzers used in this study update output signals (instrument response) once every ten seconds. By modifying electronic processing controls, instrument response can be updated at one second intervals. The improved resolution would allow for better time series alignment with co-located CO_2 measurements and improve overall NO and CO_2 correlations.

[36] Tethered balloon flights were labor intensive and very difficult to perform on a routine basis at night. Furthermore, flights can not be performed very near the roadway due to air turbulence and safety considerations, and suitable flight areas will probably not be present near most roadway test locations.

General Considerations

The NO/CO2 ratios technique for estimating "in-use" emissions could be an effective tool for evaluating demanded power as a heavy-duty vehicle modal emissions predictor. Future roadway tests incorporating this method should attempt to evaluate emission factors for other operating modes, and determine whether or not the results presented herein are reproducible at a different roadway location with similar demanded power characteristics (i.e. road grade, speed-acceleration distribution).

Further evaluation of demanded power estimates should also be investigated. Previous roadway tests indicate that demanded power can be reasonably estimated by estimating the tractive force acting upon the truck. Data requirements necessary for developing demanded power distributions would include truck velocity, acceleration, and GVWR distributions, road grade, and fleet-average rolling resistance and aerodynamic drag relationships.

Although such information may be difficult to obtain, future roadway tests should also place a greater emphasis on obtaining vehicle registration data. Current investigations on-going at Georgia Tech have found that heavy-duty trucks lack unique markings that might assist in tracing vehicle registration information and researchers are currently examining alternative identification methods. Manufacturer's data obtained through vehicle registrations would be used to better characterize subfleet distributions (model years, unladen vehicle weights) and other engine characteristics (g/bhp-hr

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[37] It was assumed that the air mass near the roadway is well-mixed, and that the average concentration along any vertical axis could be approximated by a single measurement.

emission factors, presence of emission control technologies). Coupled with traffic counts collected during roadway tests, vehicle registration data could assist in the comparison of engine dynamometer emission factors with emission factors developed based on roadway data (and assumed fleet-average BSFC data).

Using the NO/CO_2 ratios method, investigations should be undertaken to assess whether or not emission factors can be estimated for individual trucks. Many instances were encountered during sampling periods where trucks passed through the test site separated from other traffic by large distances. If registration data can be collected, comparisons between emission factors estimated based on roadway data and new engine dynamometer tests could be performed for individual trucks. Furthermore, it may also be possible to estimate CO emission factors in these instances (using a similar CO/CO_2 ratio approach).

Also for comparison purposes, future analyses should attempt to develop fleet-average engine dynamometer emission factors based on regional or national fleet and sub-fleet characteristics. This data could be used to assess relationships between emission factors developed based on roadway tests and those estimated for other fleets. If substantially different, then investigations which attempt to explain the variance would be necessary. Potential sources that might cause significant variability would include, among others, inaccurate fleet-average BSFC data and affects of engine deterioration.

The evaluation of deterioration rates based on roadway tests was not an objective of this research. However, validating the USEPA's current assumption that emissions do not increase with vehicle age is extremely important from an emissions estimation perspective. Chassis dynamometer testing may represent the only plausible means to validate or establish heavy-duty engine deterioration rates. Through a long-term test program, emission histories could be established for a fleet of vehicles by performing an annual test program. Long-haul vehicles often accrue in excess of 100,000 miles annually. Therefore, deterioration rates could be evaluated within a period of several years. Utilizing a transportable chassis dynamometer similar to the dynamometer developed at the University of West Virginia (Clark et al., 1994) could facilitate such a test program. The dynamometer could be positioned at a central depot or weight station thereby minimizing the amount of time the vehicle is out of service during the testing process.

Finally, research efforts that attempt to better quantify modal heavy-duty vehicle emission rates should also be pursued. Instrumented truck studies currently underway at the USEPA's Office of Research and Development are focusing on this need and have already yielded some interesting findings. Although only three trucks have been tested to date, modal results indicate that g/bhp-hr emission rates are probably not a constant and can vary depending on vehicle load conditions (Acurex Environmental Corporation, 1995). As more trucks are tested, researchers will attempt to establish relationships between mean emission rates as well as deviations from mean emission rates due to changes in vehicle operating conditions. Expectations are that similar relationships can be identified for groups of heavy-duty vehicles based on vehicle classification and engine technologies.

Table A.1 Instrument calibration data summary

Location/test parameter	3-4 October	4-5 October	6-7 October	8-9 October	9-10 October	10-11 October
Site 1 NO (instrument response 0 - 10 volts out)						
slope: (ppb/volt)	52.9	34.0	33.0	59.2	57.4	NO CAL
intercept: (ppb)	0.4	0.9	1.2	2.0	1.9	NO CAL
Site 1 CO_2 (instrument response 0 - 5 volts out)						
slope: (ppb/volt)	203.7	202.3	200.4	219.4	215.7	NO CAL
intercept: (ppb)	-18.0	-16.7	-16.7	-7.6	-6.8	NO CAL
Site 1 CO (instrument response 0 - 10 volts out)						
slope: (ppb/volt)	0.927	0.941	0.971	0.967	0.940	NO CAL
intercept: (ppb)	variable[a]	variable	variable	variable	variable	NO CAL
Site 2 NO (instrument response 0 - 10 volts out)						
slope: (ppb/volt)	36.7	36.5	34.2	77.6	75.9	NO CAL
intercept: (ppb)	-3.9	-2.3	-0.8	0.3	-0.4	NO CAL

NO CAL - calibration not performed, see daily measurement summaries provided in Appendix B for explanation

[a]CO instrument zero checks were performed multiple times daily; calibration data are not provided

Table A.1 Instrument calibration data summary (concluded)

Location/test parameter	3-4 October	4-5 October	6-7 October	8-9 October	9-10 October	10-11 October
Site 3 NO (instrument response 0 - 10 volts out)						
slope: (ppb/volt)	89.3	33.2	35.1	86.9	83.0	83.5
intercept: (ppb)	3.1	1.1	2.0	3.5	1.8	3.5
Site 3 CO_2 (instrument response 0 - 5 volts out)						
slope: (ppb/volt)	NO CAL	210.5	214.5	214.1	212.7	211.6
intercept: (ppb)	NO CAL	2.9	5.0	2.5	2.2	2.5
Site 3 CO (instrument response 0 - 10 volts out)						
slope: (ppb/volt)	NO CAL	0.873	0.876	0.885	0.845	0.848
intercept: (ppb)	NO CAL	variable[a]	variable	variable	variable	variable
Site 4 NO (instrument response 0 - 10 volts out)						
slope: (ppb/volt)	59.9	NO CAL	NO CAL	85.2	82.4	NO CAL
intercept: (ppb)	-0.4	NO CAL	NO CAL	1.1	1.9	NO CAL

NO CAL - calibration not performed, see daily measurement summaries provided in Appendix B for explanation
[a]CO instrument zero checks were performed multiple times daily; calibration data are not provided

Table 3.1 Daily results summary

Test Parameter		3-4 October	4-5 October	6-7 October	8-9 October	9-10 October	10-11 October
Test Period (hrs)		2000-0800	2100-0800	2000-0800	0030-0800	2000-0800	2000-0715
Traffic Summary:							
	percent test period monitored:	84.0	65.5	97.2	100	100	100
	number of trucks:	1892	1183	1469	1328	2441	2073
	number of cars:	1452	1630	2543	687	1774	2139
	average fleet fraction (as trucks):	0.60	0.47	0.45	0.71	0.63	0.54
Meteorological Summary:							
	wind direction (0-360°):	39° (NNE)	94° (E)	78° (E)	330° (NNW)	264° (W)	345° (N)
	σ_Θ (0-360°):	126°	8°	9°	10°	21°	98°
	wind speed (m/s):	1.9	4.9	3.8	1.4	1.6	2.5
	σ_{ws}(m/s):	0.9	1.0	0.7	0.7	0.5	0.5
	nominal mixing height (m):	20-30	25-40	not detected	18-25	NM	20-30
Site 1 Measurement Summary:							
NO (ppb)	minimum:	25	8	4	21	63	55
	maximum:	250	90	166	586	661	484
	mean:	112	42	37	226	414	213
CO2 (ppm)	minimum:	371	351	345	370	361	367
	maximum:	406	368	363	431	439	407
	mean:	387	356	349	400	407	389

NM - Not Measured

Table 3.1 Daily results summary (continued)

Test Parameter		3-4 October	4-5 October	6-7 October	8-9 October	9-10 October	10-11 October
Site 1 Measurement Summary:							
CO (ppm)	minimum:	0.35	0.11	0.16	0.37	0.29	0.25
	maximum:	2.1	1.3	0.87	1.8	3.9	2.0
	mean:	0.69	0.37	0.31	0.78	0.94	0.85
Site 2 Measurement Summary:							
NO (ppb)	minimum:	13	7	4	27	154	54
	maximum:	268	178	133	721	826	525
	mean:	142	48	31	368	567	248
Site 3 Measurement Summary:							
NO (ppb)	minimum:	37	19	13	40	494	11
	maximum:	304	300	314	812	922	541
	mean:	162	103	104	342	699	157
CO2 (ppm)	minimum:	360	341	349	375	407	365
	maximum:	394	383	376	464	462	415
	mean:	377	349	357	416	440	385

Table 3.1 Daily results summary (concluded)

Test Parameter		3-4 October	4-5 October	6-7 October	8-9 October	9-10 October	10-11 October
Site 3 Measurement Summary:							
CO (ppm)	minimum:	NM	0.21	0.12	0.53	0.41	NM
	maximum:	NM	1.0	1.2	1.5	1.8	NM
	mean:	NM	0.56	0.30	0.94	0.90	NM
Site 4 Measurement Summary:							
NO (ppb)	minimum:	8	NM	NM	7	339	NM
	maximum:	333	NM	NM	785	961	NM
	mean:	102	NM	NM	267	683	NM

NM - Not measured

Table 3.3 Instrumented truck results summary

GVW (lb)	Test runs	Demanded power (bhp)	Speed (mph)	Acceleration (mph/s)	Fuel economy (miles/gallon)	NO_x emission factor (g/bhp-hr)	(g/hr)	(g/mi)
28220	1-1	267	68.3	-0.108	8.72	5.95	1590	23.3
	1-2	273	68.2	-0.092	7.59	5.82	1590	23.3
	1-3	286	69.6	-0.077	3.76	5.63	1610	23.1
	2-1	258	62.4	-0.006	3.87	8.83	2280	36.5
	2-2	254	62.6	-0.014	3.80	8.49	2150	34.4
	2-3	236	61.1	-0.056	4.24	8.88	2100	34.3
	3-1	193	54.7	-0.074	4.38	10.3	1990	36.4
	3-2	208	55.4	-0.018	4.09	10.4	2150	38.9
	All data:	247	62.8	-0.055	5.06	8.05	1940	31.3
51830	1-1	314	65.5	-0.252	3.57	6.16	1940	29.5
	1-2	324	65.9	-0.246	3.71	5.73	1860	28.1
	1-3	335	66.2	-0.231	3.68	5.47	1830	27.7
	2-1	327	60.4	-0.128	3.41	6.95	2270	37.7
	2-2	319	60.1	-0.138	3.42	7.23	2310	38.4
	2-3	318	59.1	-0.124	3.40	7.52	2390	40.5
	3-1	308	54.2	-0.047	3.01	5.77	1780	32.8
	3-2	319	55.2	-0.045	3.13	5.13	1640	29.7
	3-3	306	55.0	-0.051	3.11	5.30	1620	29.4
	All data:	319	60.2	-0.141	3.38	6.14	1960	32.6

Table 3.3 Instrumented truck results summary (concluded)

GVW (lb)	Test runs	Demanded power (bhp)	Speed (mph)	Acceleration (mph/s)	Fuel economy (miles/gallon)	NO_x emission factor (g/bhp-hr)	(g/hr)	(g/mi)
75440	1-1	327	61.1	-0.321	3.49	6.14	2010	32.9
	1-2	340	63.4	-0.336	3.04	5.62	1910	30.1
	1-3	347	64.6	-0.350	3.52	5.30	1840	28.5
	2-1	322	52.2	-0.195	3.59	6.61	2130	40.1
	2-2	332	56.0	-0.240	3.28	6.79	2260	40.3
	2-3	343	56.5	-0.214	3.28	6.52	2240	39.6
	2-4	321	55.6	-0.260	3.25	6.59	2120	38.1
	2-5	328	55.5	-0.229	3.25	5.65	1860	33.4
	2-6	323	55.3	-0.244	3.23	6.01	1940	35.1
	All data:	331	57.8	-0.265	3.33	6.14	2030	35.4

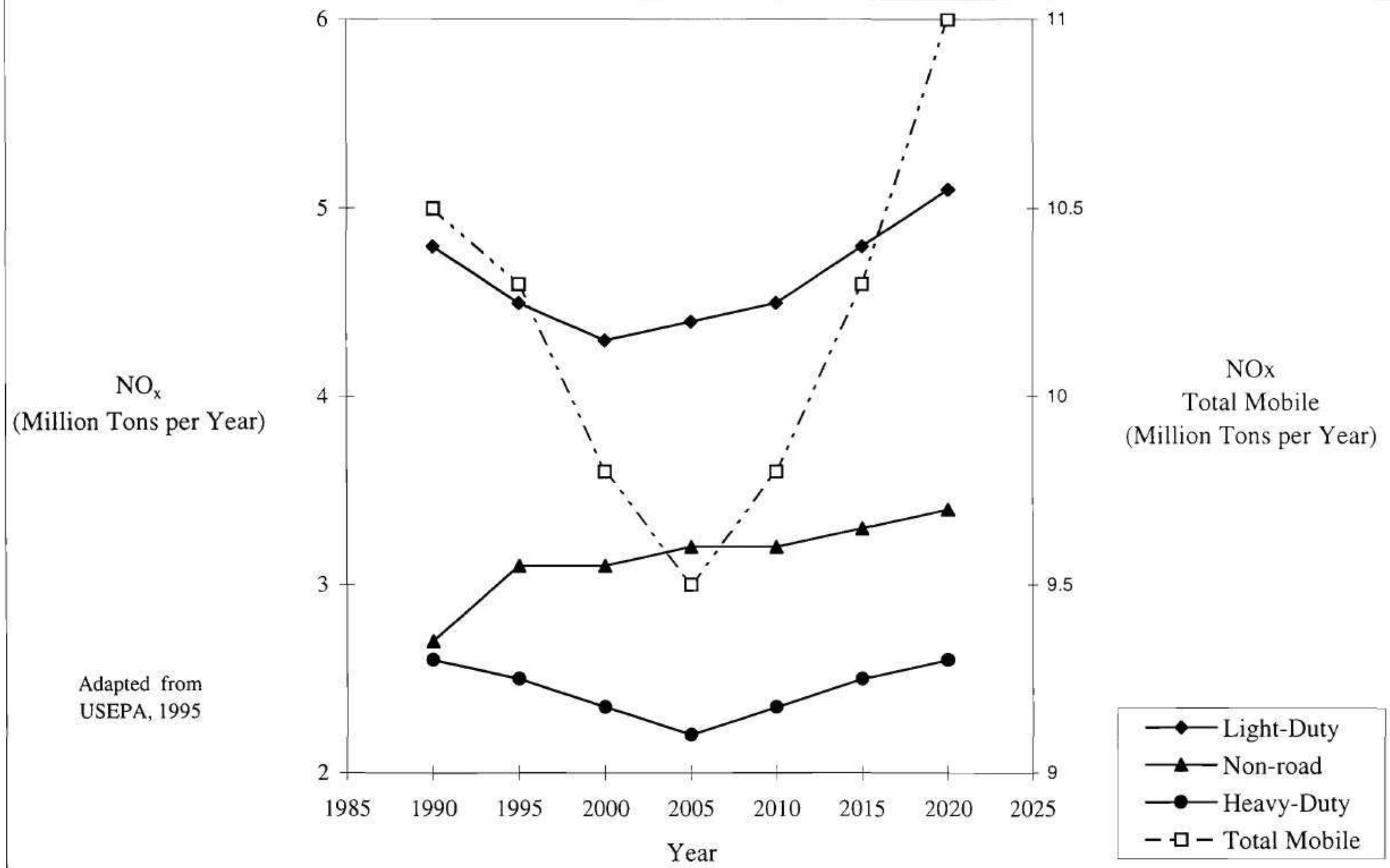

Figure 1.1 NO$_x$ emissions from transportation sources, projectected to 2020

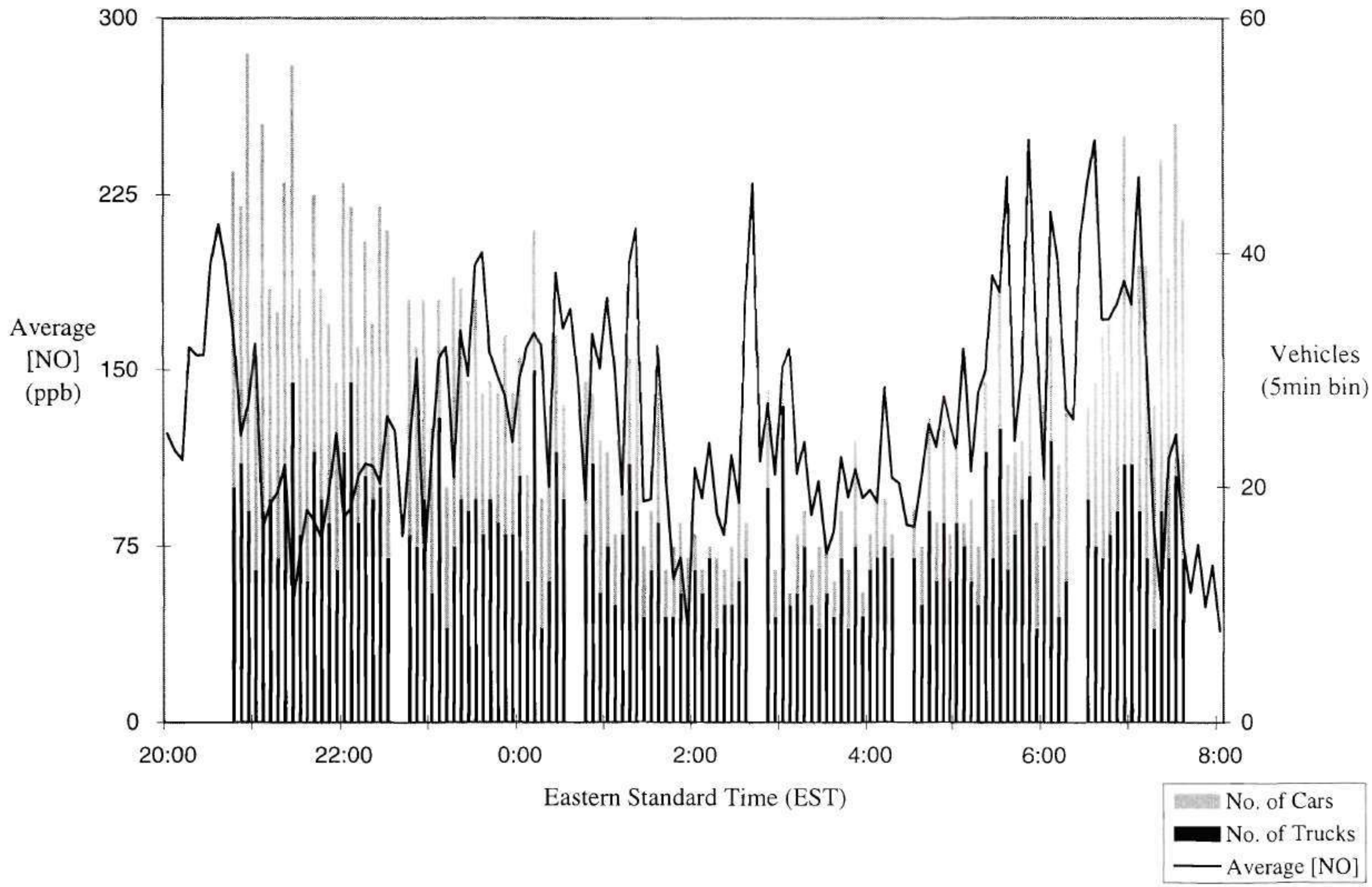

Figure 3.4(a) Vehicle acitivity and average NO concentration data; 3-4 October, 1996

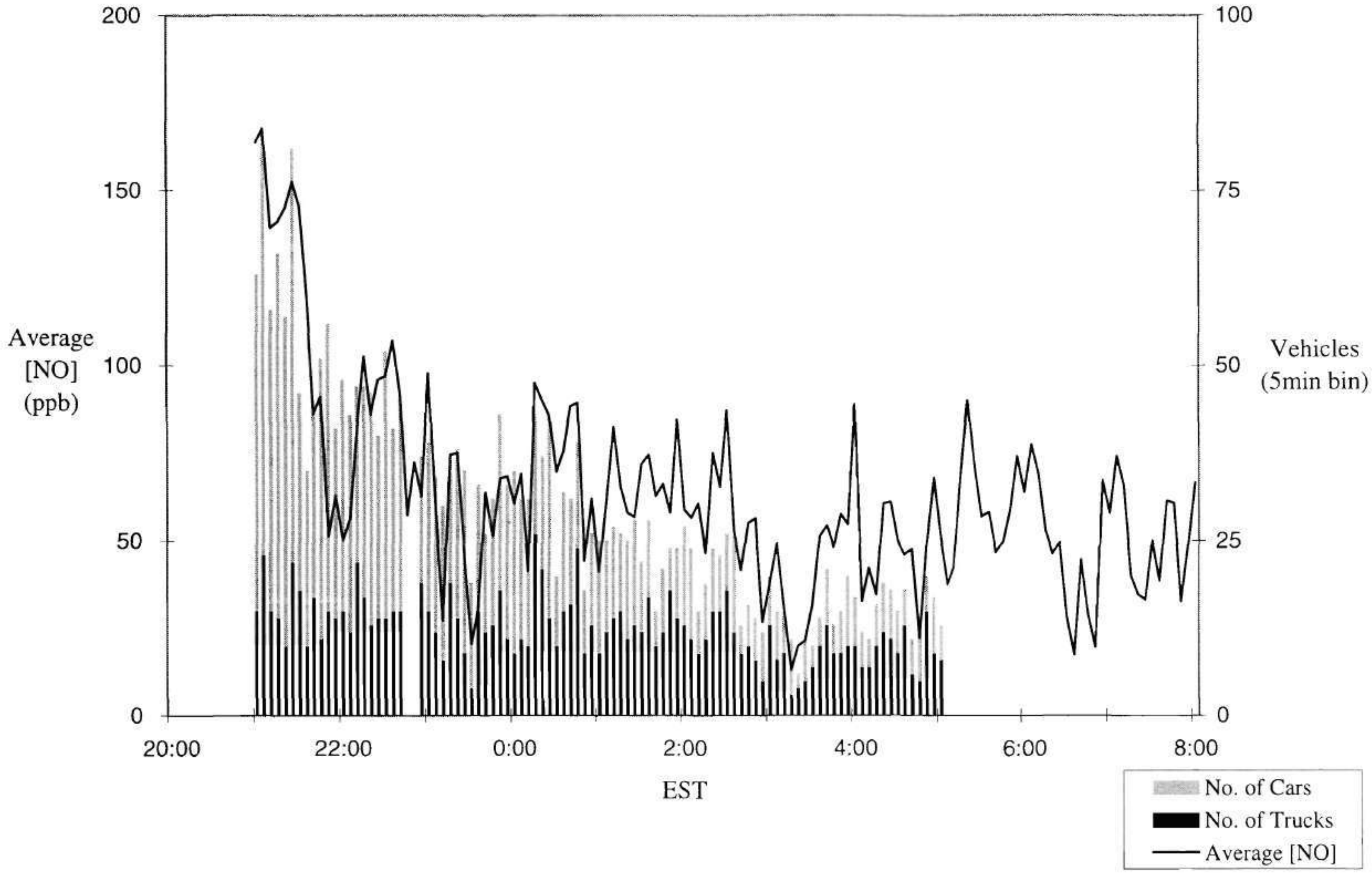

Figure 3.4(d) Vehicle acitivity and average NO concentration data; 4-5 October, 1996

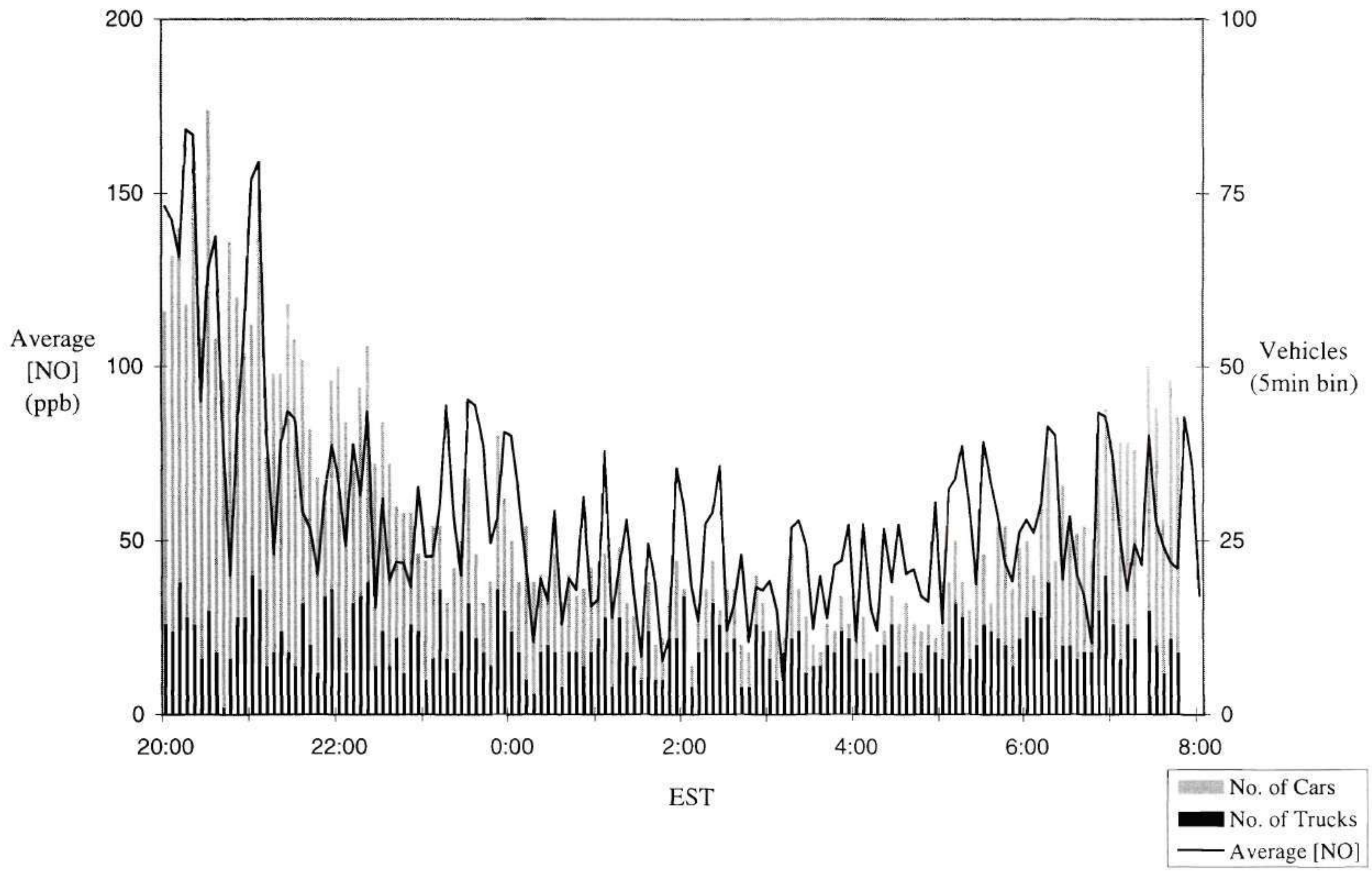

Figure 3.4(g) Vehicle acitivity and average NO concentration data; 6-7 October, 1996

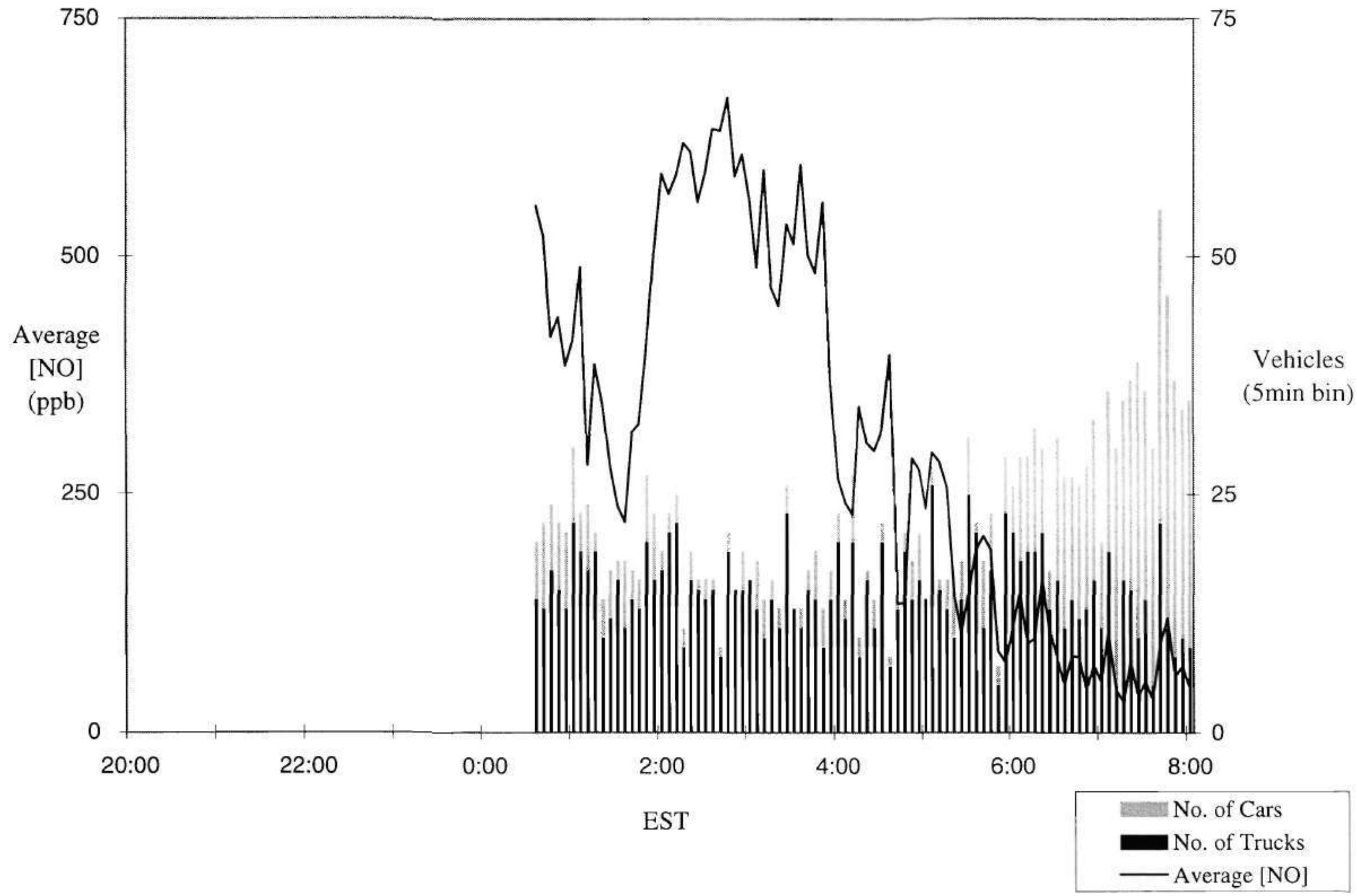

Figure 3.4(j) Vehicle acitivity and average NO concentration data; 8-9 October, 1996

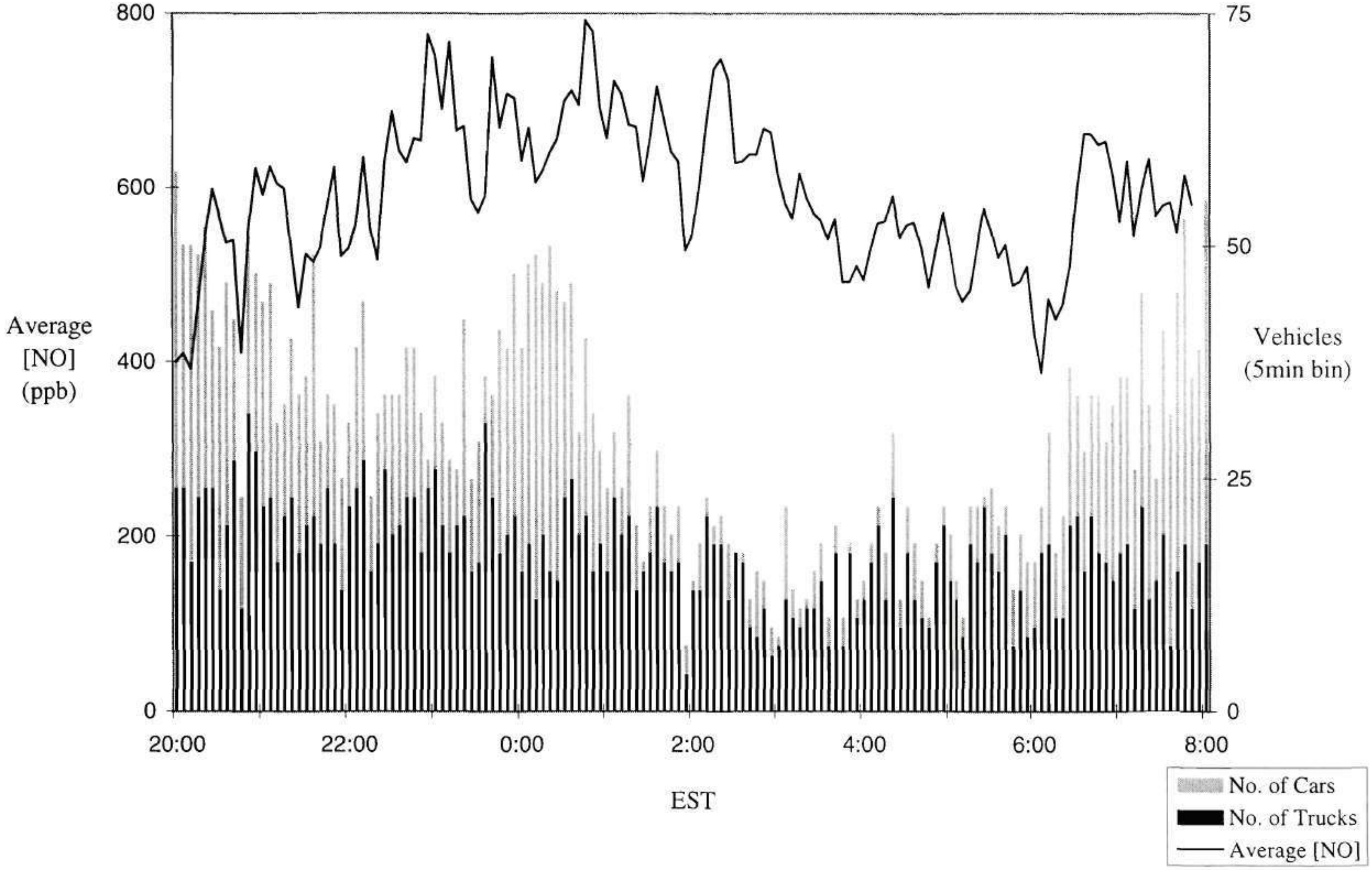

Figure 3.4(m) Vehicle acitivity and average NO concentration data; 9-10 October, 1996

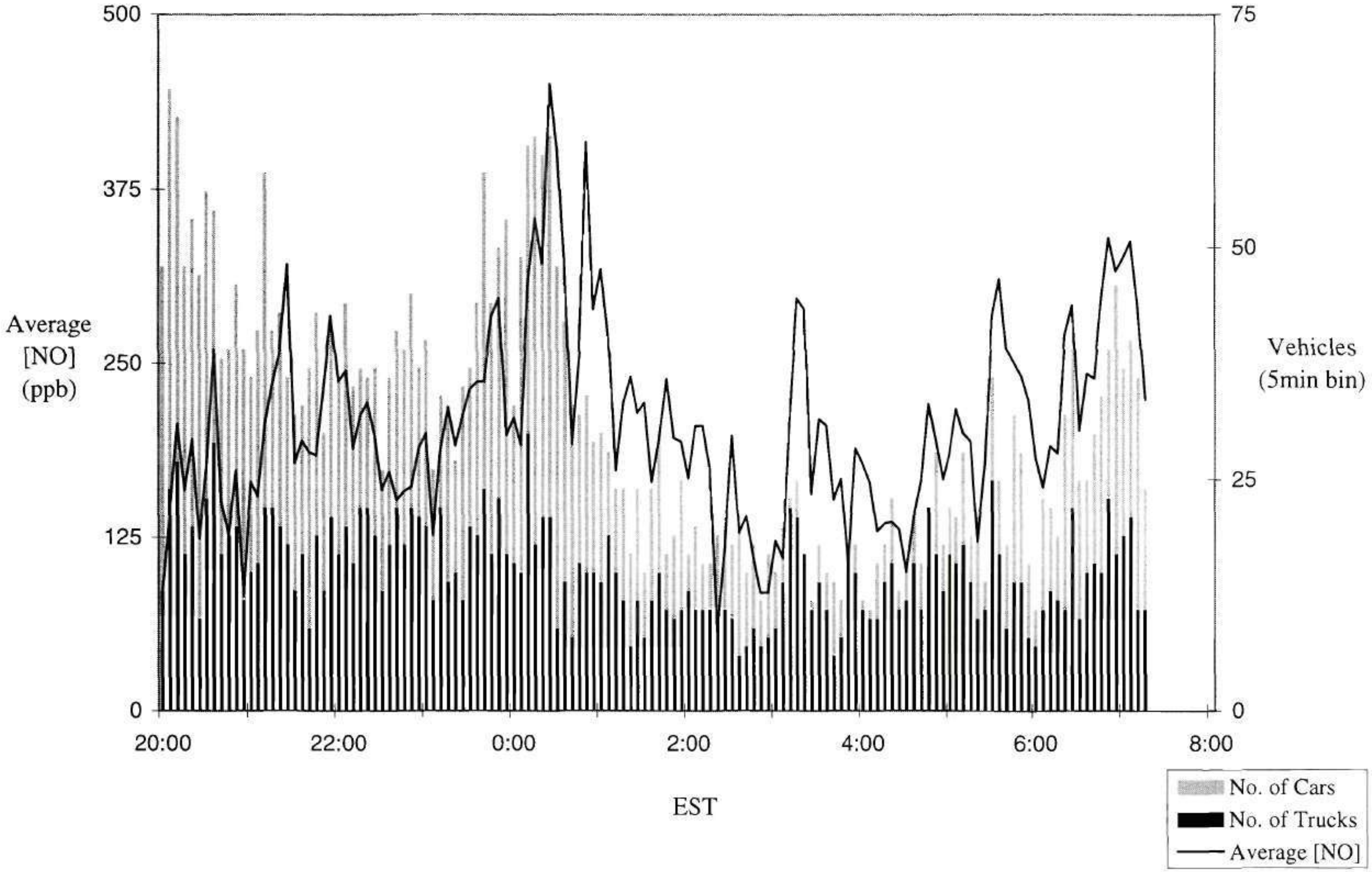

Figure 3.4(p) Vehicle acitivity and average NO concentration data; 10-11 October, 1996

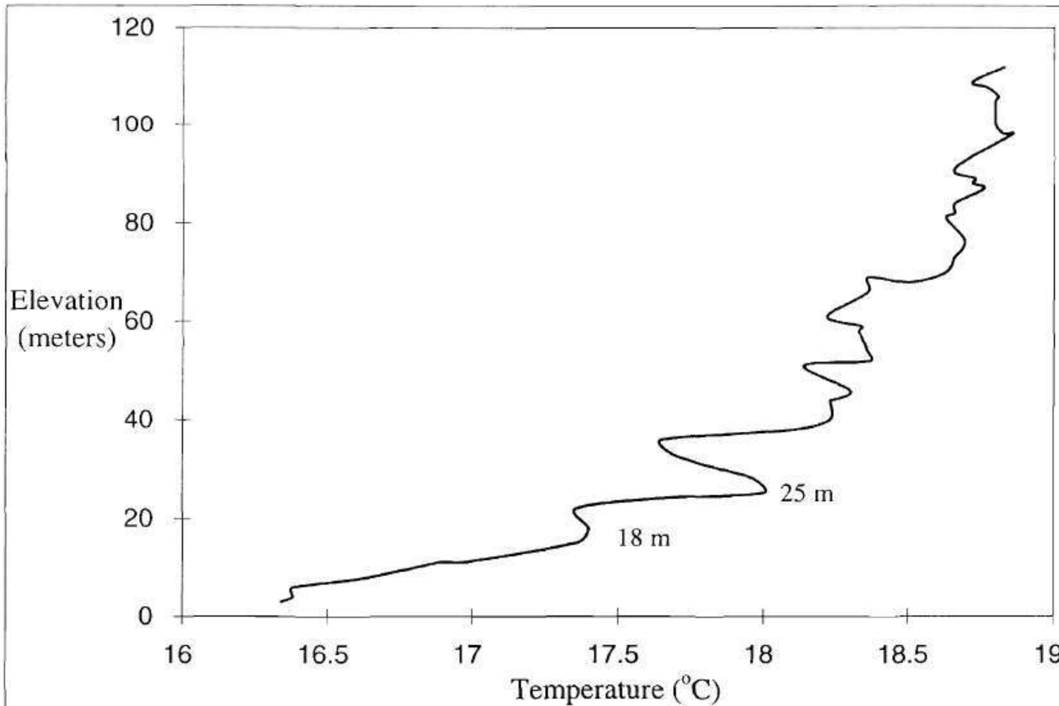

Figure 4.1 Vertical temperature profile; 8 October, 20:15 hours

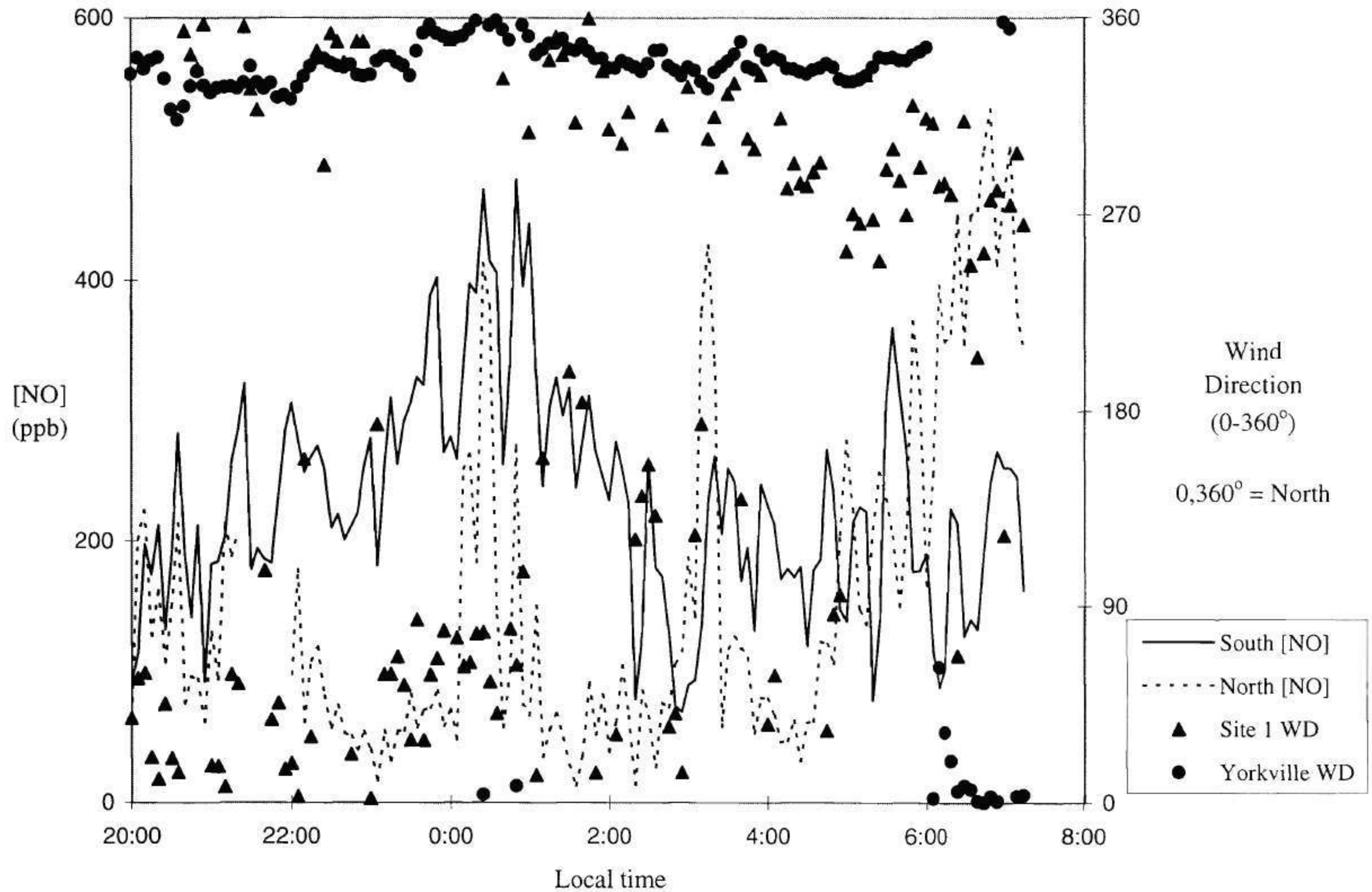

Figure 4.2 [NO] and wind direction data; 10-11 October

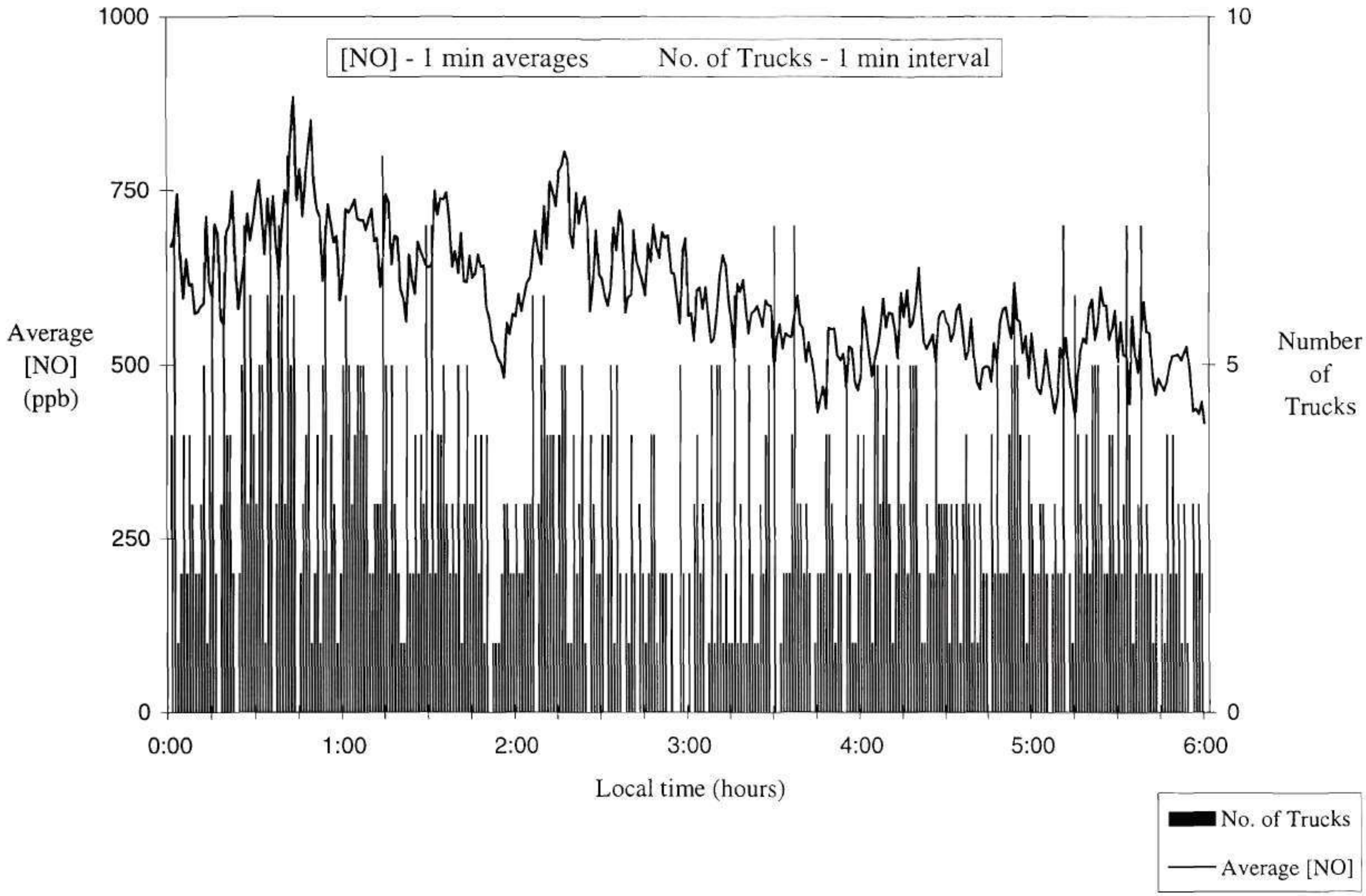

Figure 4.3(a) Average [NO] and number of truck correlation (1 minute intervals); 10 October

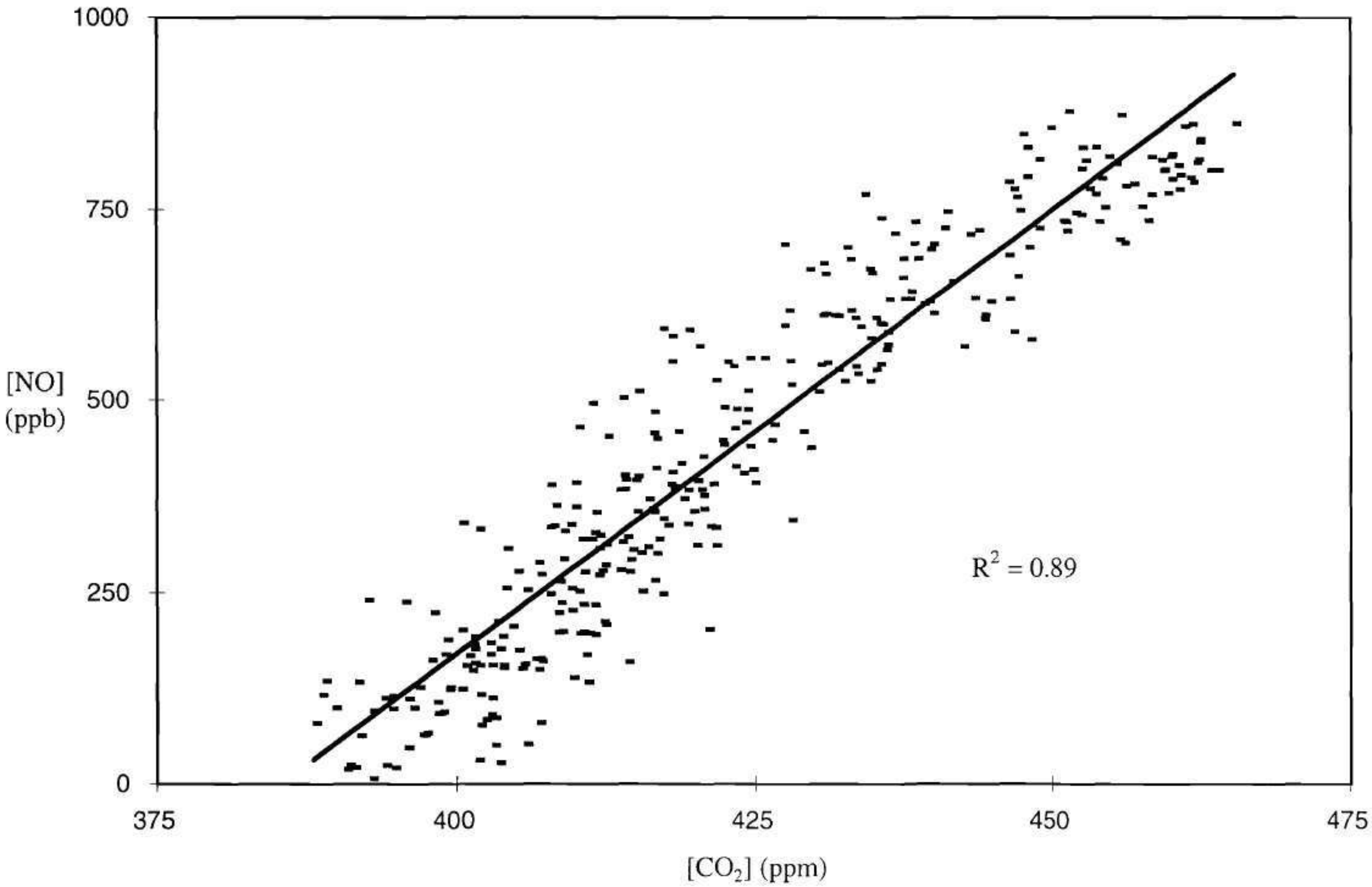

Figure 4.4 Plot of co-occuring NO and CO_2 measurements; 9 October, Site 3

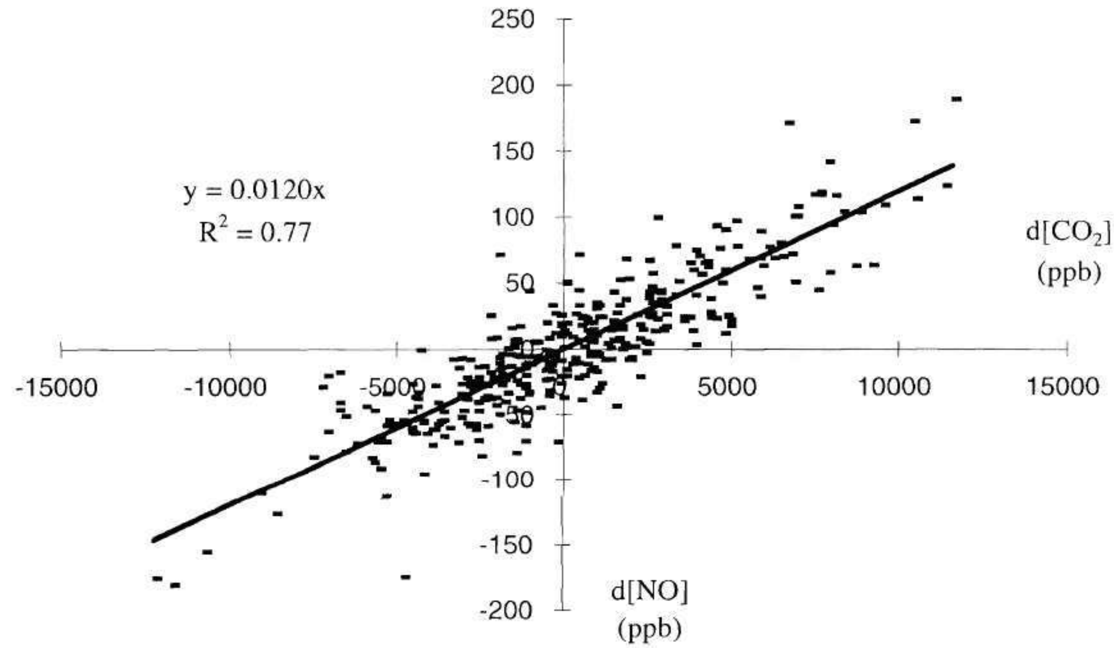

Figure 4.6 dNO/dCO_2 linear relationship; 7 October, Site 3